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NCHRP Report 398

Quantifying Congestion

Volume 1

Final Report

Transportation Research Board
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Report 398

Quantifying Congestion

Volume 1

Final Report

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration, U.S. Department of Transportation.

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FOREWORD

By Staff
Transportation Research Board

This final report reviews the state of the practice in congestion measurement, describes why a jurisdiction should measure congestion, describes how a congestion measurement program should be organized, and discusses how to interpret the measures of congestion. It will be useful to those responsible for developing a congestion management or measurement program.

In recent years, congestion on streets and highways has grown to critical dimensions in many areas of the United States. This congestion has become a major problem and has many detrimental effects including lost time, higher fuel consumption, more vehicle emissions, increased accident risk, and greater transportation costs. The concept of congestion as a serious problem has been embraced by the media, the public, policy makers, and transportation professionals. However, there is no consistent definition of congestion in terms of a single measure or set of measures that considers severity, duration, and spatial extent. Quantification of congestion on individual facilities or for individual trips, measurement of the rate of change of congestion within an area, and comparison of congestion severity, extent, duration, and variability between areas are very difficult. Accurate measures of congestion are needed for analytical purposes, such as system evaluation and improvement prioritization, and for use by policy makers and the public.

Under NCHRP Project 7-13, the Texas Transportation Institute and its consultants reviewed definitions of congestion, evaluated different measures of congestion, developed methods to obtain the recommended measures, and prepared a final report and user's guide. The report and user's guide were extensively tested and validated by the researchers' close interaction with various jurisdictions to ensure that the report and user's guide would be useful to practitioners.

The two documents present a cost-effective procedure for accurately and consistently measuring congestion of one or several modes on a roadway. The procedure provides methods to evaluate and compare congestion on corridor, subarea, and regional bases and is sensitive to both recurring and incident congestion. The procedure generates measures that are useful and understandable to policy makers and the public. While directly applicable to roadways, the procedure produces measures that can be calculated for other modes allowing easy comparisons to be made for multimodal systems.

The companion user's guide *(NCHRP Report 398, Volume 2)* describes how to measure congestion in the field (including determining the number of samples that should be collected), presents methods for estimating congestion when field measurement is not possible or practical, and describes different ways to present congestion measures so that they are understandable to policy makers and the public. Each document includes a summary of the information in the companion document.

QUANTIFYING CONGESTION
FINAL REPORT

SUMMARY

The concept of measuring traffic congestion has evolved over the past several decades. At the same time, congestion has "evolved" from a condition afflicting only central cities to a pervasive metropolitan problem. NCHRP Project 7-13, *Quantifying Congestion,* was assigned the task of developing methods to measure congestion on roadway systems. Its goals were to develop methods that are both reliable and understandable; can apply to a route, subarea, corridor, or entire urban region; can relate to simple and easy-to-obtain parameters; and can be forecast.

The measures and methods described in this report focus on the needs for congestion and mobility information. This project investigated the range of uses, users, and audiences that are associated with congestion and mobility information to determine which measures would best satisfy the range of needs. The measures and data collection procedures center on the use of travel time-related procedures. There are also methods to adapt existing volume count and capacity estimation procedures to prepare congestion estimates in appropriate formats.

CONGESTION MEASUREMENT CONTEXT

The uses for congestion measures include the traditional capacity improvement, alternatives analysis and operations evaluation studies, and a wide range of planning and policy evaluations and public outreach activities that may not usually be considered. Table S-1 identifies several types of evaluations and the uses for congestion measures. The evaluation of new infrastructure traditionally has used volume and capacity data, and these have been effective because of the type of solutions being analyzed, but the set of solutions is much greater now. The policy and program studies require a broader set of measures that illustrate the effect of congestion mitigation actions beyond volume and capacity impacts.

The traffic volume and roadway capacity-based measures work well for many purposes and will be used by many agencies for a long time. The needs for congestion and mobility are changing, however, and multimodal analyses will be a much greater part of the analysis landscape. Project 7-13 examined this landscape by separating consideration of data collection procedures and performance measures. While data collection concerns are important, the separation of the two concerns results in a system that solves the problems of transportation

TABLE S-1 Cross-classification of uses of congestion measures

USES	Monitoring & Needs Studies	Design & Operations Analyses	Evaluation of Alternatives	TDM, TSM, TCP, & Policy Studies	Development Impact Evaluations	Route & Travel Choice	Education
Identification of problems	X	X	X	X	X	X	X
Basis for government action/ investment/policies	X	X	X	X	X		X
Prioritization of improvements	X		X	X			X
Information for private sector decisions	X	X	X	X	X	X	X
Basis for national, state, regional policies and programs	X			X	X		X
Assessment of traffic controls, geometrics, regulations, improvements		X	X				X
Assessment of transit routing, scheduling, stop placement		X	X				X
Base case (for comparison with improvement alternatives)	X	X	X	X	X	X	X
Inputs for transportation models			X	X	X	X	X
Inputs for air quality and energy models		X	X	X	X		X
Measures of effectiveness for alternatives evaluation		X	X	X	X	X	X
Measures of land development impact				X	X		X
Input to zoning decisions					X		X
Basis for real-time route choice decisions						X	X

professionals and others for measurement techniques and can be consistent with data concerns. A desirable set of measures is based on the ability to satisfy the needs for information.

Measures related to travel time and speed are the most flexible and useful for a wide range of analyses. This information is used by professionals, is readily understood by the public, and is appropriate for a broad range of contexts. Increased public participation in the transportation decision-making process requires a set of performance measures that can be easily communicated. Congestion and mobility statistics are used in evaluating existing and future conditions; changes due to construction, operational improvements, and management alternatives; policy or land use decisions; and a wide range of person and freight movement analyses. Travel time measures are consistent, address transportation and land use systems, and are responsive to concerns of residents, businesses, and travelers.

These uses and needs also suggest defining congestion by focusing on the effect—an increase in travel time beyond that acceptable to travelers. The research identified two definitions:

- Congestion is travel time or delay in excess of that normally incurred under light or free-flow travel conditions.
- Unacceptable congestion is travel time or delay in excess of an agreed-upon norm. The agreed-upon norm may vary by type of transportation facility, travel mode, geographic location, and time of day.

These two definitions were used in conjunction with the measurements to develop a program of congestion measurement techniques.

The concept of defining an unacceptable level of congestion is important to the application of travel time-based measures. An acceptable travel speed or travel time can be used to identify locations where the transportation system needs improvement. The acceptable speed or time may be different in downtowns than in suburbs and will certainly be different for travel on freeways and streets. The determination of the acceptable levels might require a more extensive and interactive public communication process, but the result will be a set of indicators that can be used in evaluations and project prioritization.

Two other useful concepts also were defined in the research—mobility and accessibility:

- Mobility is the ability of people and goods to move quickly, easily, and cheaply to where they are destined at a speed that represents free-flow or comparably high-quality conditions.
- Accessibility is the achievement of travel objectives within time limits regarded as acceptable.

Accessibility can illustrate the effect of a wide range of multimodal and intermodal transportation improvements, as well as changes in land use patterns that reduce the need for long-distance trips.

CONGESTION MEASURES

Travel time and delay are the foundation for congestion measurement, but many different measures are useful depending on the need. Table S-2 summarizes several important measures that can be used in multimodal and single-mode analyses. The application of these measures at various scales and types of analysis is summarized in Tables S-3 and S-4. The rate-based quantities are typically more useful for small analysis areas or single roadways. They are also used in aggregate analyses, but magnitude quantities like total delay, or relative measures such as accessibility and indices, are more useful for their ability to relate modes and facilities with different performance characteristics.

While it is difficult to conceive of a single value that will describe all of the travelers' concerns about congestion, there are four components that interact in a congested roadway or system. These components are duration, extent, intensity, and reliability. They vary among and within urban areas—smaller urban areas, for example, have shorter durations than larger areas. Table S-5 provides an overview of ways to examine these four components:

- **Duration**—This is defined as the amount of time congestion affects the travel system. The peak hour has expanded to a peak period in many corridors, and congestion studies have expanded accordingly.
- **Extent**—This is described by estimating the number of people or vehicles affected by congestion, and by the geographic distribution of congestion.
- **Intensity**—This is the severity of the congestion that affects travel. It is typically used to differentiate between levels of congestion on transportation systems and to define the total amount of congestion.
- **Reliability**—This key component of congestion estimation is described as the variation in the other three elements. Daily congestion delay caused by excessive traffic volume is relatively stable and somewhat predictable. Nonrecurrent (due to accidents, vehicle breakdown, weather, etc.) delay causes much greater variation in the amount of congestion and is much less easily predicted. Reliability is the impact of nonrecurrent congestion on the transportation system.

TABLE S-2 Quick reference guide to measures of congestion

TRAVEL RATE	$\underset{\text{(minutes per mile)}}{\text{Travel Rate}} = \frac{\text{Travel Time (minutes)}}{\text{Segment Length (miles)}} = \frac{60}{\text{Average Speed (mph)}}$
DELAY RATE	$\underset{\text{(minutes per mile)}}{\text{Delay Rate}} = \underset{\text{(minutes per mile)}}{\text{Actual Travel Rate}} - \underset{\text{(minutes per mile)}}{\text{Acceptable Travel Rate}}$
TOTAL DELAY	$\underset{\text{(vehicle-minutes)}}{\text{Total Segment Delay}} = \left[\begin{matrix}\text{Actual}\\ \text{Travel Time}\\ \text{(minutes)}\end{matrix} - \begin{matrix}\text{Acceptable}\\ \text{Travel Time}\\ \text{(minutes)}\end{matrix}\right] \times \underset{\text{(vehicles)}}{\text{Vehicle Volume}}$
CORRIDOR MOBILITY INDEX	$\text{Corridor Mobility Index} = \frac{\underset{\text{(persons)}}{\text{Passenger Volume}} \times \underset{\text{(mph)}}{\text{Average Travel Speed}}}{\text{Normalizing Value (e.g., 25,000 for streets, 125,000 for freeways)}}$
RELATIVE DELAY RATE	$\text{Relative Delay Rate} = \frac{\text{Delay Rate}}{\text{Acceptable Travel Rate}}$
DELAY RATIO	$\text{Delay Ratio} = \frac{\text{Delay Rate}}{\text{Actual Travel Rate}}$
CONGESTED TRAVEL	$\underset{\text{(vehicle-miles)}}{\text{Congested Travel}} = \text{Sum of all}\left(\begin{matrix}\text{Congested}\\ \text{Segment Length}\\ \text{(miles)}\end{matrix} \times \begin{matrix}\text{Traffic Volume}\\ \text{(vehicle)}\end{matrix}\right)$
CONGESTED ROADWAY	$\underset{\text{(miles)}}{\text{Congested Roadway}} = \text{Sum of all Congested Segment Lengths (miles)}$
ACCESSIBILITY	$\underset{\text{(opportunities)}}{\text{Accessibility}} = \sum \text{Objective fulfillment opportunities (e.g., jobs), where Travel time} \le \text{Acceptable travel time}$

The Final Report and User's Guide detail the application of the various congestion measures to several typical analyses. The examples stress the importance of matching the measures with the type of problem, audience, and information needs. Several multimodal and operating strategy examples illustrate the selection of measures and the interpretation of congestion information to evaluate and prioritize transportation improvements.

DATA COLLECTION AND ANALYSIS

It is recommended that travel time and speed studies should be used to collect congestion data directly whenever feasible. These data can be used to quantify congestion, identify bottlenecks in traffic systems, evaluate computerized coordinated traffic signal systems and other operational improvements designed to move traffic more efficiently, provide data for air quality analyses, and improve analyses and feasibility studies for a range of multimodal and intermodal improvements.

TABLE S-3 Recommended congestion measures for various levels of analysis

Level or Scale of Analysis	Measures of Congestion										
	Travel Time	Travel Time Difference	Travel Rate	Delay Rate	Total Delay	Relative Delay Rate	Delay Ratio	Corridor Mobility Index	Congested VMT/ PMT	Congested Roadway	Accessibility
Individual Locations	S	S			P						
Short Roadway Sections	P		P	P	S	S					
Long Roadway Sections or Routes		S	P	P	P	S	S				
Corridors			S	S	P	P	P	S			S
Sub-Areas					P			S	P	P	P
Regional Networks					P			S	P	P	P
Modal Analyses		P	S	S	P	P	P	P			P

Note: P = Primary measure of congestion
S = Secondary measure of congestion
VMT = Vehicle-miles of travel
PMT = Person-miles of travel

Traffic counting programs also can be more effectively targeted when system bottlenecks are identified. If the goal of the analysis is to identify the areawide magnitude of congestion, the severity of the problem and the location of the most significant congested areas, the process should start with the local transportation experts identifying the known congested areas and, in at least a general way, categorizing their severity. For corridor, subarea, or regional analyses, travel speeds then can be sampled on a few routes in the same way that traffic counts are sampled. Travel time data also can be collected in conjunction with traffic counts.

The research team gathered travel speed, roadway inventory and traffic volume information from 15 urban areas in the United States. The data were used to identify variations in travel times, develop data collection requirements, and derive surrogate speed estimation for freeways and arterial streets.

SAMPLING PLANS

Sampling plans were developed for estimating (1) the number of travel time runs needed on a particular roadway segment and (2) the number of roadway segments that should be studied in an areawide congestion analysis. They were based on the variation of travel times (or speeds) for time periods and for roadway systems.

- The suggested number of travel time runs to quantify congestion on particular street and freeway segments is shown in Tables S-6 and S-7.
- Travel speed variation was analyzed for roadways with similar traffic volume and geometric characteristics. The number of roadway segments that should be sampled to estimate congestion levels for studies that cover areas rather than individual roads is related to this variation.

ESTIMATING TRAVEL SPEED

For situations in which direct data collection is not possible, the research identified several surrogate speed estimation techniques.

TABLE S-4 Recommended congestion measures for various types of analyses

Uses of Congestion Measures	Measures of Congestion										
	Travel Time	Travel Time Difference	Travel Rate	Delay Rate	Total Delay	Relative Delay Rate	Delay Ratio	Corridor Mobility Index	Congested VMT/ PMT	Congested Roadway	Accessibility
Identification of problems	P	P	P	P	S						
Basis for government investment or policies					P			S	P	P	P
Prioritization of improvements				P	P	P	P		S	S	S
Information for private sector decisions	P		P	P	S						
Basis for national, state, regional policies and programs					P				P	P	P
Assessment of traffic controls, geometrics, regulations	P		P	P		S	S				
Assessment of transit routing, scheduling, stop placement	P	P	P	P	S						
Base case (for comparison with improvement alternatives)		P		S	P			P			P
Inputs for transportation models	P		P	P							
Inputs for air quality and energy models	P		P	P							
Measures of effectiveness for alternatives evaluation			P	P	P			P			P
Measures of land development impact	P	S	P	P	P						P
Input to zoning decisions	P	P	P								P
Basis for real-time route choice decisions	P	S	P	P							

Note: P = Primary measure of congestion
S = Secondary measure of congestion
VMT = Vehicle-miles of travel
PMT = Person-miles of travel

TABLE S-5 Overview of methods to measure congestion aspects

Congestion Aspect	System Type		
	Single Roadway	Corridor	Areawide Network
Duration (e.g., amount of time system is congested)	Hours facility operates below acceptable speed	Hours facility operates below acceptable speed	Set of travel time contour maps; "bandwidth" maps showing amount of congested time for system sections
Extent (e.g., number of people affected or geographic distribution)	% or amount of congested VMT or PMT; % or lane-miles of congested road	% of VMT or PMT in congestion; % or miles of congested road	% of trips in congestion; person-miles or person-hours of congestion; % or lane-miles of congested road
Intensity (e.g., level or total amount of congestion)	Travel rate; delay rate; relative delay rate; minute-miles; lane-mile hours	Average speed or travel rate; delay per PMT; delay ratio	Accessibility; total delay in person-hours; delay per person; delay per PMT
Reliability (e.g., variation in the amount of congestion)	Average travel rate or speed ± standard deviation; delay ± standard deviation	Average travel rate or speed ± standard deviation; delay ± standard deviation	Travel time contour maps with variation lines; average travel/time ± standard deviation; delay ± standard deviation

Note: VMT—vehicle-miles of travel
PMT—person-miles of travel

Freeways

The best predictor of speed on freeways uses daily traffic volume per lane and access frequency (Equation S-1). Separate equations were developed for freeways that account for the effects of freeway bottlenecks. The model is described in Equations S-2 and S-3.

$$\begin{aligned} \textit{Peak Hour Speed (mph)} &= 91.4 - 2.0\,[\textit{ADT/Lane}, 1000s] \\ &\quad - 2.85\,[\textit{Access Frequency (access points per mile)}] \end{aligned} \tag{S-1}$$

TABLE S-6 Suggested travel time variations and approximate sample sizes for arterial streets

Signal Density Group	Average c.v. (%)	Minimum runs for 80%, 10%[a]	Minimum runs for 85%, 10%[b]	Minimum runs for 90%, 10%[c]	Minimum runs for 95%, 5%[d]
Low—less than 3 signals per mile	9	2(6)[e]	2(6)[e]	3(6)[e]	13
Medium—3 to 6 signals per mile	12	3(6)[e]	3(6)[e]	4(6)[e]	23
High—greater than 6 signals per mile	15	4(6)[e]	5(6)[e]	7	35

[a] 80% level of confidence, 10% relative error—runs calculated using Equation 20 (normal distribution).
[b] 85% level of confidence, 10% relative error—runs calculated using Equation 20 (normal distribution).
[c] 90% level of confidence, 10% relative error—runs calculated using Equation 20 (normal distribution).
[d] 95% level of confidence, 5% relative error—runs calculated using Equation 20 (normal distribution).
[e] Six runs needed to provide reasonable assurance that data are not affected by unusual conditions (e.g., driver behavior, signal malfunctions).

TABLE S-7 Suggested travel time variations and approximate sample sizes for freeways

ADT per Lane Stratum Group	Average c.v. (%)	Minimum runs for 80%, 10%[a]	Minimum runs for 85%, 10%[b]	Minimum runs for 90%, 10%[c]	Minimum runs for 95%, 5%[d]
Low—less than 15,000	9	2(5)[e]	2(5)[e]	3(5)[e]	13
Moderate—15,000 to 20,000	11	2(5)[e]	3(5)[e]	4(5)[e]	19
High—greater than 20,000	17	5	6	8	45

[a] 80% level of confidence, 10% relative error—runs calculated using Equation 20 (normal distribution) .
[b] 85% level of confidence, 10% relative error—runs calculated using Equation 20 (normal distribution).
[c] 90% level of confidence, 10% relative error—runs calculated using Equation 20 (normal distribution).
[d] 95% level of confidence, 5% relative error—runs calculated using Equation 20 (normal distribution).
[e] Five runs needed to provide reasonable assurance that data are not affected by unusual conditions (e.g., driver behavior).

$$\textit{Effective ADT per Lane} = \textit{Bottleneck ADT/Lane}\ [W_1 - W_2 \times d] \qquad \text{(S-2)}$$

where

W_1 = weighting factor for magnitude of bottleneck = 1.1 (1.4 when ADT per lane exceeds 30,000),
W_2 = weighting factor for distance to bottleneck = 0.1, and
d = distance to beginning of bottleneck

$$\textit{Peak-Hour Speed (mph)} = 86.4 - 1.5\ [\textit{Effective ADT/Lane}, 1000s] - 2.85\ [\textit{Access Frequency (access points per mile)}] \qquad \text{(S-3)}$$

Arterial Streets

For arterial streets, traffic volume per lane (or volume-to-capacity ratio), traffic signal density, and signal progression were found to be key factors in estimating speed. Figures S-1 and S-2 illustrate the relationship between traffic volume, signal density, and speed for Class I and Class II/III arterials.

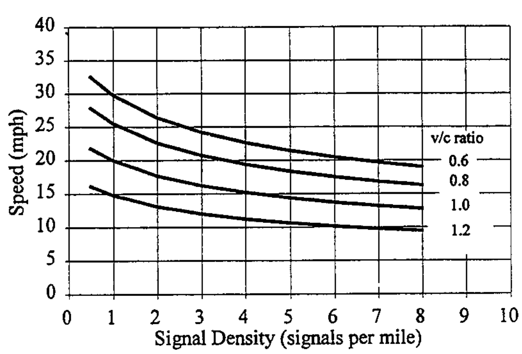


Figure S-1. Suggested speed estimation curves for Class I arterials.

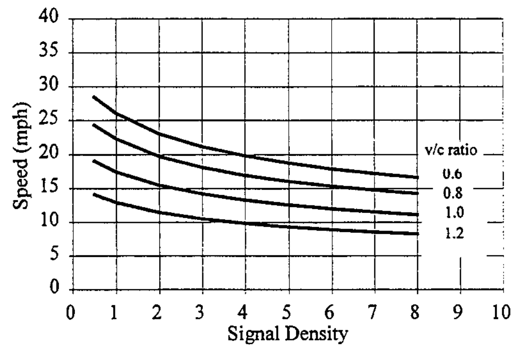


Figure S-2. Suggested speed estimation curves for Class II/III arterials.

Equations S-4, S-5, and S-6 can be used to estimate traffic speed. The effective signal density factor accounts for the influence of signal progression on travel speed. Equation S-7 illustrates the calculation of effective signal density.

The speed estimates in these equations account for signal progression. The effective signal density represents the signals per mile times [1 − (Through Band Capacity/Cycle Length)].

All Arterials. Using the Volume-to-Capacity Ratio

$$\text{Peak-Hour Speed (mph)} = \frac{60}{\left(\dfrac{60}{\text{Free-Flow Speed (mph)}}\right)\left(\begin{matrix}1 + \text{Effective}\\ \text{Signal Density}\end{matrix}\right)^{0.3}[1 + (v/c)^4]^{0.7}} \quad \text{(S-4)}$$

where v/c = volume-to-capacity ratio

Class I Arterials. Using ADT/Lane as a Surrogate for the *v/c* Ratio

$$\text{Peak-Hour Speed (mph)} = \frac{60}{\left(\dfrac{60}{\text{Free-Flow Speed (mph)}}\right)\left(\begin{matrix}1 + \text{Effective}\\ \text{Signal Density}\end{matrix}\right)^{0.3}\left(1 + \left(\dfrac{\text{ADT/Lane}}{10{,}000}\right)^4\right)^{0.7}} \quad \text{(S-5)}$$

Class II/III Arterials. Using ADT/Lane as a Surrogate for the *v/c* Ratio

$$\text{Peak-Hour Speed (mph)} = \frac{60}{\left(\dfrac{60}{\text{Free-Flow Speed (mph)}}\right)\left(\begin{matrix}1 + \text{Effective}\\ \text{Signal Density}\end{matrix}\right)^{0.3}\left(1 + \left(\dfrac{\text{ADT/Lane}}{8{,}000}\right)^4\right)^{0.7}} \quad \text{(S-6)}$$

$$\text{Effective Signal Density} = \left(\begin{matrix}\text{Signal Density}\\ \text{(signals per mile)}\end{matrix}\right)\left(1 - \dfrac{\text{Through Band Duration (seconds)}}{\text{Cycle Length (seconds)}}\right) \quad \text{(S-7)}$$

When future speed estimates are required for existing roadways, Equation S-8 can be used to take advantage of recent travel time studies. Surrogate travel speed estimates are developed for both the existing and future conditions using the equations derived from a national data set (Equations S-4, S-5, and S-6). These estimates are combined with the existing directly collected travel speed to produce a speed estimate that is consistent with current local conditions.

$$\mathit{Future\ Estimate} = \mathit{Existing\ Measurement} \times \frac{\mathit{Future\ Surrogate}}{\mathit{Existing\ Surrogate}} \qquad \text{(S-8)}$$

CONGESTION INDEX CONCEPT

A congestion index that attempts to reflect motorists' perceptions of traffic congestion was presented to assist in communicating information on traffic congestion levels and to promote further discussion on congestion indices. This "speed reduction index" reflects the ratio of the *relative speed* change between congested and free-flow conditions. This index, shown in Figure S-3 ranges from 0 to 10, with congestion usually occurring when the index exceeds 4 to 5 (a 40 percent to 50 percent drop in speed).

CONCLUSIONS

This report describes methods of estimating congestion from the perspective of the uses, users, and the audience for congestion information. If the wide range of analyses that rely on congestion information and the interests of the audiences are included in the assessment of congestion measurement techniques, measures that are related to person or freight movement and travel time, speed, or rate will be the most useful.

The direct data collection methods and surrogate speed estimation techniques address the data collection concerns and provide a link to historic and current congestion quantification techniques. Considering the data collection needs and limitations after the measures are identified will result in information that directly addresses the requirements of the analysis.

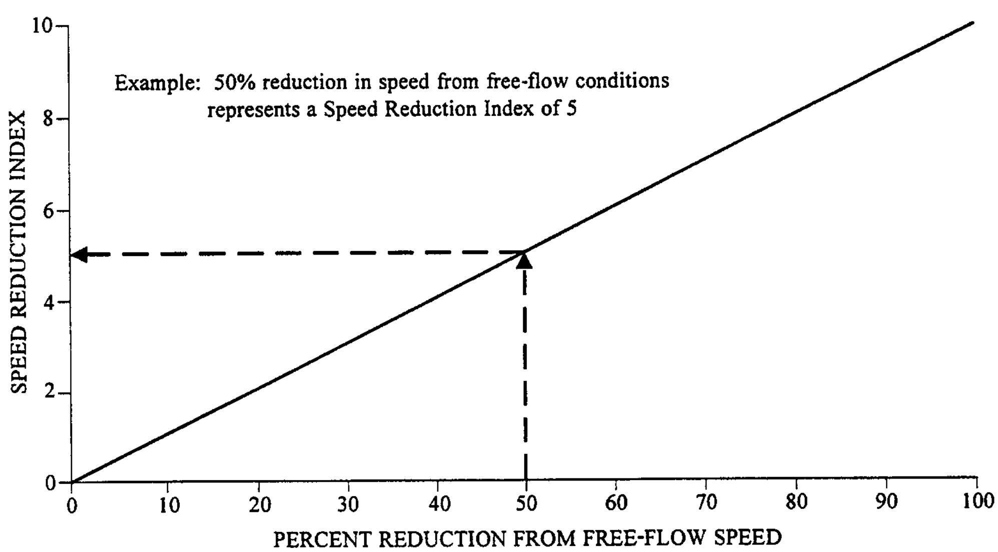


Figure S-3. Speed reduction index.

Any compromises that become necessary to fit data collection concerns or budgets can be made with due consideration of the congestion measurement needs.

The range of modal improvements, strategies, and policies that are considered in modern transportation analyses requires flexible measures that can provide common quantities. The effect of each proposed solution should be reflected in the measures chosen to represent the results of improvement analyses. The measures should also relate the analysis to the goals and objectives of the transportation system and the land use patterns it serves. These "reality checks" are necessary for effective communication between the various groups involved in transportation decisions.

RECOMMENDATIONS

Several recommendations emerged for improving congestion measurement.

- The audience for congestion measures should be clearly recognized.
- Transportation professionals in charge of data collection activities should be targeted for an information campaign about the results of this research.
- The development and application of congestion measurements should not be solely a function of easily obtained data.
- Multimodal analyses will require the use of common denominators that facilitate comparisons and evaluate the effectiveness of the transportation system at meeting the assigned travel objectives.
- Both multimodal and mode specific analyses will be required in many situations.
- The effort of the intended improvement should be quantified in the chosen measure or measures.
- The congestion measurements should illustrate quantities that are consistent with the goals and objectives of the transportation system and the related land-use regulations or plans.
- Agencies should be encouraged to directly collect peak and off-peak travel time information on a systematic basis—such as developing peak and off-peak travel time contours from the city center or other important activity centers.

Additional research should be encouraged in several areas. These include

- Improving travel time estimation and validation processes for computerized urban transportation planning programs.
- Applying and refining the congestion index concept.
- Assessing the effects of improved traffic signal coordination on travel speeds.
- Further analyzing the effects of bottlenecks on freeway congestion.
- Improving estimates of the effects of incidents on freeway operations.
- Performing behavioral studies to assess the reactions of travelers to various levels of congestion.

CHAPTER 1

CURRENT PRACTICE AND FUTURE NEEDS FOR CONGESTION MEASUREMENT

THE NEED FOR CONGESTION MEASUREMENT

NCHRP Project 7-13, *Quantifying Congestion,* was charged with developing ways to reassess and enhance congestion measurement. The research was conducted in context with the changed policy environment arising from national concerns about air quality and energy use, detrimental effects of congestion on the economy and land development, and citizen frustration with driving conditions and impacts on quality of life. The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) and revisions to the Clean Air Act reflect and mandate the new policy environment and prescribe congestion monitoring and management for which existing measurement procedures are not well suited.

The growth of traffic congestion on many streets and highways is a major concern to travelers, administrators, merchants, developers, and to the community at large. Its detrimental impacts in longer journey times, higher fuel consumption, increased emissions of air pollutants, greater transport and other affected costs, and changing investment decisions increasingly are recognized and felt across the country. Congestion reduces the effective accessibility of residents, activities, and jobs and results in lost opportunities for both the public and business.

Congestion in central cities has been recognized for some time, and is one of the reasons residents and businesses moved to the suburbs. Congestion now has reached the suburbs as well. This would appear to leave metropolitan areas with choices of limiting growth, controlling travel demand, spending massive amounts of money for highway or transit improvements in built-up areas, or watching current suburbs decay and the central city decay more while residents and businesses continue with the next phase of the dispersion cycle. The effects of inaction have been felt by city tax bases and they are beginning to affect suburbs' revenues as well.

Despite these effects and resulting concern and discussion, action has been slow in coming. There has been little concerted nationwide effort other than activities under the heading of intelligent transportation systems. Congestion and growth problems require more effective solutions than old remedies are able to deliver. There is need to measure their extent and impacts better.

The ISTEA legislation and related regulations did, however, provide formal impetus for progress. Its provisions embrace an array of new approaches and shifts in emphasis that have been enacted in several local processes. ISTEA included mandates for transportation planning that consider methods to reduce and prevent congestion, including transportation and land use management, enhancement of transit services, reduction of single-occupant motor vehicle travel, and construction of new transportation facilities through use of innovative financing mechanisms. ISTEA also called for management systems that include traffic monitoring for highways, intermodal transportation systems, and public transportation. The regulations developed in response to the legislation focused on providing deadlines, information, and flexibility to local and state agencies. The precise construction of congestion measurement and analysis techniques was left to the preparers of the management systems.

Mitigating congestion by managing traffic better, expanding transport capacity, managing travel demands, or modifying land use requires basic information on how, where, why, and to what extent congestion occurs. But these congestion mitigation efforts can succeed only with an organized and focused effort that begins with universally understood and accepted definitions of congestion and consistent means of measurement. Despite its pervasive nature, there are relatively few consistent definitions and systematic measures of congestion.

The current state of uncertainty about congestion measurement is caused not by any profound inability of the traditional highway capacity-oriented measures of the past four decades to perform the tasks they were designed for. Change is coming because the uses to which performance measures are being put have been broadened. The goals and objectives they are being paired with have been augmented or changed. A measure perfectly designed to gauge achievement of smooth vehicular flow is not necessarily going to be a good measure for assessing satisfaction of need for reasonable access to jobs, goods, and services with the least social cost. It may not even be a good measure for gauging achievement of maximum roadway person-throughput under monetary or right-of-way availability constraints. In addition, a measure designed to assess performance at an individual location may not be suited to assess congestion along a route or within an area.

The Importance of Context

It is essential, therefore, that performance measures be consistent with the goals and objectives of the process in which they are being employed. Performance measures are key to controlling process outcome, whether the process is alternative selection, congestion management, growth management, or system optimization. For example, within congestion management, performance measures are used for problem identification and assessment, evaluation and comparison of alternative strategies, demonstration of effectiveness, and ongoing system monitoring.

Poor selection of measures has a high probability of leading to poor outcomes. In contrast, goals and objectives properly paired with performance measures provide the mechanism whereby decision makers can guide planners and engineers toward achieving desired ends and can then check (using evaluation results) that the desired ends are in fact best served by the solutions offered (*1*). Thus, the context for measuring and assessing congestion is important.

Congestion is, however, only one of many performance measures. The measures of congestion recommended in this report are optimal for a wide range of uses, but they must be combined with others to fully describe the operating condition of transportation systems and the service provided to travelers. Level-of-service and vehicle density, for example, can be used as congestion measures, but they also describe some aspects of quality and comfort of the service provided by the facility as perceived by the traveler. Creating a set of congestion measures does not require consideration of these other concerns.

An Example of Analytical Challenges

It does not take congestion mitigation, intelligent transportation systems, or growth management considerations to illustrate the changes that have taken place and the analytical challenges faced by transportation professionals. Consider project planning for a hypothetical 5-mi section of freeway. It is theorized that an additional lane or lanes may improve traffic flow in this section. Volume counts are taken at three locations on the freeway mainlanes and at all entrance and exit ramps to calculate volume-to-capacity ratios in an effort to understand the existing situation. The critical sections are identified, and an additional lane is recommended for 3 mi, and auxiliary lanes are recommended for two locations.

Now suppose that environmental or financial concerns prevent this solution from being implemented. It is suggested that operational improvements may provide some benefit. Ramp metering with bus and carpool priority bypass lanes, increases in transit service in the corridor, and an incident detection and response system are considered as a means to improve mobility without any additional freeway mainline capacity. The proposed improvements affect the amount of incident delay differently from recurrent delay, and they attempt to reduce delay for higher occupancy vehicles more than for single-occupant vehicles (SOV), which may lead to shifts in the travel mode percentage.

Simple volume-to-capacity ratio calculations cannot be used to quantify and illustrate the effect of these new improvements because they do not recognize increased vehicle capacity or the delay reduction achieved by the operational strategies employed. Volume-to-capacity ratios are also difficult to express in person-movement terms or to aggregate to peak period analyses. Density measures also have many of these problems. Therefore, additional approaches are necessary and desirable.

OVERVIEW OF THIS RESEARCH EFFORT

Thus, there is a need for a congestion definition(s) that is(are) reliable; can be understood by the general public; can be applied to a route, subarea, or entire urban region; can be forecast; and, if possible, can be related to simple and easy-to-inventory parameters. Measures are needed that define the quality of traffic flow and can be used in the travel demand forecasting process to establish needs or priorities for improvements and for developing community support for transportation improvement proposals. They also should support practitioners and researchers by enhancing comprehension of congestion phenomena and their management in producing effective solutions to traffic flow, mobility, and transportation operations and systems deficiencies. Both definitions and measures are needed that can meet new ISTEA and Clean Air Act requirements and be an effective means of communicating congestion problems and their potential solutions to policy makers and the public.

This research report and the associated User's Guide describe a process to quantify or estimate congestion that satisfies the diverse needs of users, is oriented to the knowledge base of a wide variety of audiences, and is consistent with needs for estimating congestion and mobility associated with multimodal transportation systems.

Much of the project effort focused on developing roadway congestion measures and estimation techniques. Some of these will be useful for the analysis of congestion and mobility provided by other modes, but in general the study of non-roadway congestion has been left for other researchers. The roadway congestion measures have been designed, however, in context with multimodal evaluation needs.

SCOPE OF CONGESTION MEASUREMENT

The scope of congestion measurement is both broad and multidimensional. The specifications of any particular application will be dictated by the users of congestion measurement and the uses they apply. The users and uses of congestion measures are the subject of the next section. The uses described there indicate that congestion measures will be needed for different kinds of facilities, at various times of the day, and in assorted locations and contexts that vary according to the urban or rural character of the area under analysis.

The breadth of existing and potential applications places special demands on congestion measurement because it imposes need for flexibility of application in an environment where consistency among applications is likewise very important. The sometimes conflicting requirements between flexibility and consistency form the basis of some of the key congestion measure evaluation criteria described in Chapter 2.

Table 1 lists seven specific situations that significantly influence the scope and nature of congestion measurement: scope, locus, mode, roadway type, time of day, planning context, and level of detail.

Geographic Scope

Two aspects of location must be considered when measuring congestion—geographic scope and locus. Geographic scope identifies the spread and extent of the area to be represented and investigated. The scope can range from an individual intersection to an urban area, a state, or the whole country. It is important to define the boundaries of a corridor or subarea by the travel patterns within the corridor or subarea, not just by the extent of congestion alone, which could bias the results. Other areas of analysis are much more readily defined by physical or political limits.

Locus

The other aspect of location to consider is where and in what type of area the congestion occurs. The political boundaries of the central city and incorporated suburban cities make it easy to define the location of congestion in those areas. Other location descriptions are more difficult to clearly establish because the boundaries between them are more subjective. Guidelines for establishing those boundaries, based on the character of development and traffic, are provided here.

The central business district (CBD) core should be defined by its dramatically higher density of development than elsewhere in the metropolitan area. The central city comprises the areas outside the core where there is reasonably consistent nature and density of development, even though this area may have scattered pockets where development and density vary. The CBD fringe is the transitional area between the core and the central city, where density decreases and development character changes.

Incorporated suburbs, the cities and towns surrounding the central city, include both residential and commercial land uses. Major activity concentrations, the so-called "edge cities," require differentiation from their surroundings just as CBDs do. Edge cities are identifiable places with commercial activity of about the same magnitude as CBDs—with more jobs than population, and more density than their sur-

TABLE 1 Situations where congestion may be measured

GEOGRAPHIC SCOPE Intersection/Interchange Facility Segment Route/Corridor Sector/Subregion Region State/Nation	LOCUS CBD Core CBD Fringe Central City Suburbs Suburban Fringe Seasonal/Resort Stadium, Arena or Sports Complex
TRANSPORTATION MODE Roadways HOV or Bus-Only Lanes Car Pools Buses Rail in Roadway or Median Exclusive Guideway Transit	ROADWAY TYPE Freeways and Toll Roads Expressways and Super Arterials Principal Arterials Minor Arterials Collectors Local Streets
TIME OF DAY/DAY OF WEEK Morning Peak Afternoon Peak Noon Peak Midday Evening Daily Average Weekday Average Special Events Holiday or Weekend	PLANNING CONTEXT Existing Conditions Existing Demand/Modified Supply Future Demand/Existing Supply Future Year Conditions LEVEL OF DETAIL Policy Planning Design Operations (Also see Users and Uses)

roundings. They occur in incorporated and unincorporated suburbs and also inside of central cities.

Suburban development that has not incorporated can be defined by comparing the consistency of its character and density with incorporated suburbs. If there are no incorporated suburbs, suburban development can be defined by the age and character of structures and possibly by density or lot sizes. The suburban fringe is where development density decreases from the more consistent density of the suburbs. Seasonal or resort areas outside cities will require different treatment from traditional urban locations. Other rural locations may also have to be addressed if they demonstrate, or may demonstrate, congested conditions.

Transportation Mode

Congestion is experienced and may have to be measured for all modes of transportation. Congestion is most often thought of as only a roadway phenomenon, but it occurs for transit as well. In fact, the effects of congestion on commercial and multioccupant vehicles, whether transit or car pools, should be considered more serious than congestion of SOVs. Bus traffic and light rail transit systems may experience congestion in the CBDs of large cities. These modes also experience and cause congestion on major roadways. Despite the best efforts of transit operators, exclusive guideway transit can also experience congestion during periods of heavy demand especially on older systems with design deficiencies and complex system configurations. Even high-occupancy vehicle (HOV) lanes may have congestion caused by lane discontinuity or problems of entry and exit.

Roadway Types

The more commonly experienced congestion occurs on roadways. Different measurement strategies may need to be considered for different types of roadways because of variations in the physical condition and the character of traffic carried by each. Freeways and toll roads are sufficiently similar to be considered in the same manner, although toll roads, including those with automatic vehicle identification (AVI), have readily available traffic measurement capabilities. Expressways and regional arterials also have relatively uninterrupted flow and other similar characteristics that permit them to be addressed in the same manner.

Principal and minor arterials may have to be treated separately because of their different level and character of traffic and because they commonly have different capacities. These facilities require much more intense congestion measurement because their traffic is affected by so many intersections and access points from adjacent development.

Time of Day

Another dimension of congestion to consider is when it occurs and how much it varies. The number of different times to consider will differ with the level of congestion experienced. The most frequently observed and greatest level of congestion usually occurs during the morning and afternoon peak periods. Whether to consider a peak 15-minute period, single peak hour, or a multiple-hour period will be dictated by the use intended for the congestion measure and the specific urban setting involved. For air quality concerns, the duration of the congestion period is needed, but a measurement of the congestion in the peak hour is often sufficient for transportation planning and traffic analysis. The afternoon peak (and noon peak if it exists) consists of a greater variety of trips, many of which are difficult to analyze because of their mixed purposes and multiple stops. As a result, the morning peak is sometimes preferred for analysis as it is more nearly uniform, consistent, and predictable. In a few large central business districts, it may be desirable to assess congestion throughout the working day. It is also important to analyze the effect of incidents on congestion variability.

It is also sometimes important to measure congestion on summer or holiday weekends, special events such as football games, and major concerts. Congestion in these situations is often more onerous because of the unexpected nature of congestion in small cities or rural areas and the sharp, peaking characteristics of certain activities.

One final period to consider is an average daily measure of congestion, using some weighting process to combine the observations during all periods of the day. Another useful approach is to describe the severity of congestion by the percentage of the day during which facilities or areas of interest are congested. These latter two presentations are particularly useful for describing congestion to the general public.

Planning Context

The planning, engineering, or policy context within which congestion measures are applied is still another dimension of the scope of congestion measurement. The four planning contexts listed in Table 1 can be defined easily using the example of transportation needs studies. Congestion measures may be used to examine need as evidenced by existing conditions of travel demand and transportation facility supply, or they may be applied to some modified context.

One modified context is that of existing travel demand and modified transportation facility supply such as would be needed to examine the needs that remain after implementation of a current improvement. Another is that of future demand and existing supply, used to answer the question of what will happen if nothing is done to accommodate traffic growth. The final context is that of future year conditions throughout; future traffic on future facilities, such as the transportation system after implementation of a capital improvements program. All modified contexts involve forecasting of either congestion alone or future traffic and congestion.

Level of Detail

Variations in level of detail do affect the scope of congestion measurement. The level of detail ranges from complex measures required by certain types of operations analyses, air quality investigations, and model inputs, to the simplified measures that are needed for conducting widespread investigations with minimum data or for explaining results to anyone not immersed in the transportation specialty. The special needs of administrators, other decision makers, the media, and the general public for measures that are readily understandable are examined further in the next section on users and uses of congestion measures. Policy and planning analyses usually require less detailed measurements than traffic operations or design.

SUMMARY OF USES AND USERS

A crucial step in the design and selection of appropriate congestion measures is a clear understanding of what role it is that they are being asked to perform. Selection of an appropriate set of congestion measures requires examining the total context in which the measures will be used, including the underlying purpose of the analysis process, the potential solutions for deficiencies under study, the needs of transportation agencies and other groups to communicate congestion information, and the knowledge base of the audiences that will receive the information.

Uses of Congestion Measures

Congestion information can be used in a variety of policy, planning, and operational situations. It may be used by public agencies in assessing facility or system adequacy, identifying problems, calibrating models, developing and assessing improvements, and formulating programs, policies, and priorities. It may be used by the private sector in making locational or investment decisions. It may be used by the general public and media in assessing travelers' satisfaction.

Table 2 offers two perspectives on uses of congestion measures and combines them into a cross-classification. The listing down the left side of Table 2 focuses on purposes to

TABLE 2 Cross-classification of uses of congestion measures

USES	Monitoring & Needs Studies	Design & Operations Analyses	Evaluation of Alternatives	TDM, TSM, TCP, & Policy Studies	Development Impact Evaluations	Route & Travel Choice	Education
Identification of problems	X	X	X	X	X	X	X
Basis for government action/ investment/policies	X	X	X	X	X		X
Prioritization of improvements	X		X	X			X
Information for private sector decisions	X	X	X	X	X	X	X
Basis for national, state, regional policies and programs	X			X	X		X
Assessment of traffic controls, geometrics, regulations, improvements		X	X				X
Assessment of transit routing, scheduling, stop placement		X	X				X
Base case (for comparison with improvement alternatives)	X	X	X	X	X	X	X
Inputs for transportation models			X	X	X	X	X
Inputs for air quality and energy models		X	X	X	X		X
Measures of effectiveness for alternatives evaluation		X	X	X	X	X	X
Measures of land development impact				X	X		X
Input to zoning decisions					X		X
Basis for real-time route choice decisions						X	X

which congestion measures are applied. Across the top are classes of studies, analyses, and endeavors that congestion measures are used in. Under each class of study, analysis, or endeavor, an "X" is entered opposite each purpose that pertains. Common to most congestion measure applications are establishment of base case conditions, identification of problems, and assessment of options for problem resolution or policy formulation.

Monitoring and Needs Studies are conducted to identify the location, scale, and nature of transportation problems and needs throughout a jurisdiction, region, operations district, or designated problem area. This type of system monitoring, once called deficiency or sufficiency studies, is a major component of the management systems that were mandated in ISTEA. Needs studies may be quite specific, reporting such matters as condition of pavement and structures, or employing congestion measures to describe adequacy of intersections and roadway sections to accommodate traffic. Alternatively, they may take a broader view, using measures of mobility or accessibility to rank the quality of transportation service offered in each sector or corridor, with corresponding identification of average and substandard conditions. Private industry uses congestion information from needs and accessibility studies in making locational decisions.

The congestion measurement employed within a needs study or management system to identify problems also provides a basis for government action and/or investment to correct the problems, including the prioritization of improvements. In addition, needs study information is vital as a basis for setting policy and developing broader programs at national, state, and regional levels. Traffic monitoring under ISTEA is obviously intended to improve the basis for policy and programming. Finally, the congestion measure results of a needs study or traffic monitoring report inherently provide a base case against which improved conditions, or conditions in other areas, can be measured.

Design and Operations Analyses are the traffic studies done in transportation system design work or in the preparation of operating plans or developing improvements. Congestion measures are used to identify specific problems and assess solutions to these problems, such as the freeway traffic weaving movement that is creating delays, the traffic signal phase lacking sufficient green time, the intersection with carbon monoxide violations, the bus trips that have too many standing persons, or the rapid transit station platform that could become dangerously overcrowded. Design and operations analyses are, for the most part, well served by the existing toolbox of mode-specific performance measures.

Evaluation of Alternatives has as obvious examples the extensive examination of alternatives done for major highway and transit projects. These processes are brought together in the joint FHWA/FTA rulemaking of October 28, 1993, "Metropolitan Planning Process: Major Metropolitan Transportation Investments," a further step into the era of multimodal alternatives analyses (*2*).

Measures of effectiveness as employed in evaluations of alternatives include measures of mobility or accessibility and other forms of congestion measures. Performance measures are used in evaluation of alternatives to establish a base case for comparison, to rank the alternatives that are studied, and to justify investment.

TDM, TSM, TCP, and Policy Studies are critical tools in congestion and air quality management. As with other studies, travel demand management (TDM), transportation systems management (TSM), transportation control plans (TCP), and policy studies use congestion measures to describe base case conditions, establish a basis for action, and set priorities. They similarly provide information for the private sector, of particular interest to businesses asked to participate in TDM or affected by TCP measures. Strategies under consideration may include alternative approaches to land use planning and site design and efforts to bring transportation performance measures into play as measures of growth management.

Development Impact Evaluations use congestion measures to identify where impacts of proposed development will cause problems and also to identify existing problem areas where development may be restricted under growth management regulations such as Adequate Public Facilities Ordinances or "concurrency" requirements for land and transportation system development. Congestion measures are used as a basis for government action in the specific case of zoning decisions and related regulation of land development, and similarly to establish policy with respect to land use and access management. Private sector land development decisions and strategies, including those of businesses that want to locate or expand, are obviously heavily influenced in turn. A difficult issue in the deployment of congestion measures in development impact evaluations is the ability to sort out the tradeoff between localized impacts, particularly those related to street traffic, and regional concerns such as multimodal transportation efficiency.

Route Choice covers both the routing and scheduling of trucks and utility vehicles and real-time route choice decisions of travelers en route. Routing and scheduling of trucks and scheduled fleets today already involve identification of congestion problems and accessibility opportunities and often employ congestion or accessibility measures into routing and scheduling models or algorithms.

Education includes both training of professionals in transportation and related disciplines, and enlightenment of administrators, public officials, the general public, and other users of congestion measures. Education inherently must involve study and explanation of all possible uses of the subject matter in question.

Users of Congestion Measures

Congestion measures and their complements, mobility and accessibility measures, are used by practically every organization, profession, and group that is involved with providing, consuming, or living next to highway transportation and public transit. Obviously, the extent and sophistication of use varies markedly, with major implications for the selection and formulation of transportation performance measures.

The professionals in engineering, planning, and related fields most likely to use congestion measures follow:

Transportation Engineers, who include traffic engineers and operations planning specialists specializing in real-time surveillance and control, and fleet vehicle scheduling and routing. Transportation engineers are primarily concerned with highway vehicles, but multioccupant and transit vehicles are included. Many of their design and operations analyses make good use of conventional capacity-based, mode-specific measures, or highly specialized real-time condition evaluation algorithms.

Transit Planners, who use some of the same measures as traffic engineers when seeking effective surface transit operation on the highway system, but also have their own mode-specific measures for addressing vehicle loading and passenger flow problems. Transit planners also have need of more generalized mobility and accessibility performance measures for evaluating the delivery of transit service.

Environmental Specialists, who have their own very specialized uses of congestion measures, primarily as input to pollutant emission and energy consumption calculation.

Transportation Planners, who have interests in congestion measures that parallel those of both transportation engineers and transit planners but with more frequent need to apply congestion measures in multimodal situations. They would find it particularly useful if there were a common measure of congestion that could be applied to examine the combined effects on person mobility of existing and proposed multimodal transportation systems and alternatives, including TDM, TSM, TCP, and land use proposals.

Land Use Planners, who use congestion measures in assessing everything from localized development proposals, where the near-term congestion impact on an adjacent intersection is the primary concern, to broad planning studies of the impact of different horizon year distributions of population and employment. Zoning and related actions often bring intense conflict between citizens and private development interests over the issue of traffic infiltration and congestion, requiring congestion measures that are simple and robust enough to provide a reliable means of communication between professional and lay persons often taking different sides in both hearings and court trials.

Instructors and Researchers, who apply congestion measures across all modes, geographic areas, time periods, conditions, and levels of detail that are the purview of the transportation specialties in which they teach or perform research.

Others besides engineers and planners use congestion measures, some of them professionals in other fields, and some as elected or appointed officials, or as persons affected by transportation systems, proposals, actions, or regulations. They include

Administrators, who must deal with congestion measures across all of the same modes, geographic areas, time periods, and conditions with which their professional staff are involved. They need robust measures that can be quickly grasped and acted upon.

Business Persons, who use congestion information at much the same level as government administrators, but from the perspective of private enterprise.

Elected/Appointed Representatives and Officials, who are in essentially the same position with respect to use of congestion measures as the administrators who serve them, except that they normally have a lesser foundation in training for understanding technical complexities. To be in a position to make informed decisions, they need simple and straightforward measures correctly matched to the implications of the transportation and land use questions brought to them for resolution.

The General Public, which uses congestion measures in efforts to understand, and particularly to assess, the impacts of pending transportation and land use decisions on their daily travel and on the quality of life in their neighborhoods. Particularly in the context of today's public involvement, congestion measures are part of the necessary communication of information and positions between transportation practitioners, administrators, and land developers on one hand and the public on the other, and between the public and their elected and appointed representatives.

Lawyers, particularly those involved with land development, who normally prefer to deal with measures of congestion that are simplified to allow easy comprehension by public officials, examiners, judges, and juries.

Media Representatives, who use congestion measures as a necessary means of communicating transportation news and opinion to the public. They report performance measures pertaining to everything from research results to public decisions and private sector development actions.

Travelers en Route, who have made travel decisions based on their qualitative perception of congestion for quite some time. With the advent of intelligent transportation systems, most particularly traveler information services, travelers will join the ranks of users employing quantitative transportation performance measures.

Conclusions

The fact that such diverse groups and institutions need to use the same information argues for congestion measures and definitions that are understandable and unambiguous. Yet, for congestion measures to serve the rigorous technical requirements of practitioners and researchers, the same measures capable of portrayal at the least common level of understanding must also be accurate, descriptive, and consistent.

DEFINITIONS OF CONGESTION, MOBILITY, AND ACCESSIBILITY

What Is Congestion?

Congestion to the traveler is immobility. It is long lines of stopped or slowly moving vehicles on a freeway, suburban highway, or city street. It is the traffic "backups" on the approach to an open drawbridge, at a bottleneck or choke point on the street system, or at a freeway lane drop due to design, accidents, or construction.

In broad perspective, congestion is caused by separation of places where people shop, work, go to school, et cetera, from where people live. It is compounded by the inability of transport investment to keep pace with travel demand. Its nature, location, and severity have been shaped by shifts in where people work, shop, and reside and how they travel among those places.

Traffic congestion usually results when (a) the road system is unable to accommodate traffic at an adequate speed, (b) there are conflicts among the different types of traffic (cars, trucks, buses, or pedestrians), and (c) traffic controls are improperly used. Often, these problems work together to create or increase congestion. Table 3 gives examples of congestion resulting from these deficiencies.

Traffic congestion may be recurrent or nonrecurrent. Recurrent congestion generally occurs at the same place, at the same time every weekday or weekend day. Nonrecurrent congestion results from incidents such as accidents or roadway maintenance.

TABLE 3 Examples of where congestion takes place

Description	Basic Cause		
	Roadway and Access Deficiencies	Traffic Mix	Traffic Controls
Major increase in land-use intensity without changes in transport capacity	X		
Insufficient road space (capacity) to accommodate demands (e.g., discharge from stadium parking area)	X		
Route convergence, lane drops, lane imbalances, and/or road narrowing resulting in increased traffic per lane (e.g., bridge or tunnel approach)	X		
Discontinuities in street system resulting in "double loading" streets and heavy turns	X		
Transition from uninterrupted (free) flow to interrupted (stop and go) flow: as at toll plazas or terminals of freeway	X		
Short weaving sections on high-speed roads	X		
Complex multiphase junctions	X		
Railroad grade crossing or drawbridge blocking traffic flow	X		X
Trucks on up-grade blocking passenger cars	X	X	
Pedestrian-bus-car conflicts at CBD junctions		X	
Ineffective traffic signal controls, uncoordinated signals, long red-times, long cycle lengths			X
Double parking (or frequent parking/unparking maneuvers) along city streets		X	
Delays associated with left turns from turns blocking through lanes; or long waits for left turns to clear	X		X
Inadequate length of transit stops—resulting in bus-bus and bus-car delays	X	X	X
Long dwell times at transit stops			X
Narrow passageways and platforms at busy rail transit stations	X		

Congestion is normally associated with the morning and evening weekday peak periods. But it also can occur on summer or holiday weekends, especially where there are many trips to and from the shore and mountains. And it also may occur before and after events such as athletic or cultural events.

Congestion manifests itself over both time and space. It may occur along short or long sections of roadway; it may occur for a few minutes, a few hours, or the entire day. Conceptually, it can be viewed as a series of contours that defines its geographic extent, duration, and intensity. The contours are similar to the freeway traffic density (vehicles per lane per mile) contours that have been used to define freeway performance and problems.

Definition of Congestion

Past definitions of congestion tend to fall into two basic categories, those that focus on cause and those that focus on effect. Congestion measurement clearly requires a definition that addresses the effect, or symptoms, of congestion. A common theme permeates most definitions of congestion that focus on effect—congestion reflects an increase in travel time or delay beyond that acceptable to travelers.

Any definition of congestion, and the congestion measures derived therefrom, should rely on concepts that are understood by the intended audience. Travel time and its related quantities are widely understood and fundamentally useful in the definition and measurement of congestion. However, the congestion reflected in travel times, rates and delays that are acceptable to travelers can vary by city size, location in the urban (or rural) area, and time of day or year. One method that may be used to resolve this issue is to define two quantities, congestion and unacceptable congestion:

- *Congestion is travel time or delay in excess of that normally incurred under light or free-flow travel conditions* (Figure 1).
- *Unacceptable congestion is travel time or delay in excess of an agreed-upon norm. The agreed-upon norm may vary by type of transportation facility, travel mode, geographic location, and time of day.*

The agreed-upon norm could reflect travel speed, travel time or delay in a range from slightly to significantly above that incurred under light or free-flow travel conditions, and should be derived taking into account the expectation for each portion of the transportation system as influenced by community input and technical considerations. The agreed-upon norm, and consequently the amount of acceptable congestion, may be varied by geographic location, time period, mode, and facility type to reflect different expectations or objectives under different conditions.

The acceptable congestion standards may have a relationship to the congestion perceived by travelers. Motorists usually are aware of congestion when travel speeds reduce to about 60 percent to 70 percent of the free-flow speeds. Communities may establish other thresholds, but they should realize that they may overstate or understate the level of congestion that motorists perceive.

Some areas may wish to link directly the values used for acceptable congestion levels to the transportation improvement process—when travel conditions fall below the agreed-upon norm an improvement is needed. An alternative is to use the exceedance of the agreed-upon norm, to indicate that an improvement is needed in the corridor or area of the deficiency, not necessarily in the travel mode or facility itself. Separating the acceptable congestion concept from the designation of an improvement may be more appropriate for

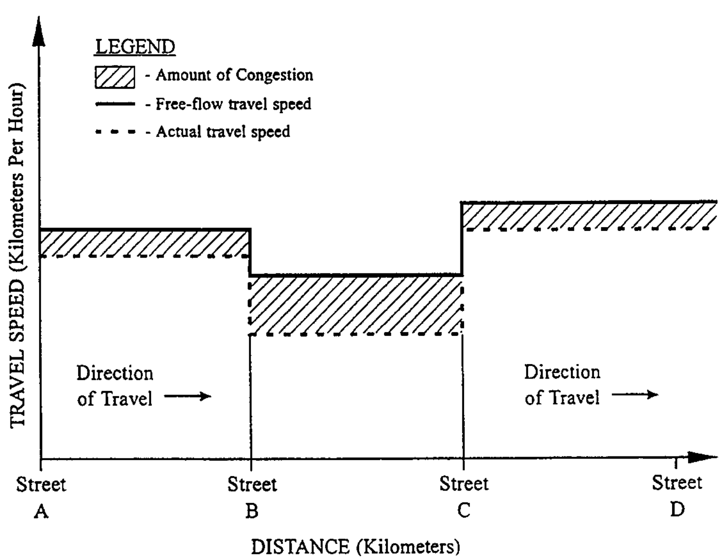


Figure 1. The definition of congestion.

areas where congestion levels are higher and multimodal alternatives are more frequently considered.

The definition of congestion in the Congestion Management System (CMS) regulations (*3*) is similar to the definition of "unacceptable congestion" above. The TTI research team believes there is a need to separate the quantities of congestion and unacceptable congestion. The definition within the CMS regulations is relevant only within the confines of the regulations rule. States and MPOs are free to adopt their own definitions and measures to meet their needs, goals, and resources.

With these congestion definitions, travel conditions may be compared for a variety of modes and system components on a more equal basis. However, it is still necessary to be aware that the role of congestion varies by mode. On most urban highways, congestion is a dominant factor in service quality; its causes are numerous. On transit systems, congestion also affects quality—it may reflect both too many vehicles on a lane or track, or too many people in each vehicle, but it may be overshadowed in importance by other transit service characteristics such as frequency, route coverage, and overcrowded vehicles or lack thereof. Up to certain limits (typically encountered only in New York City or foreign countries), more users result in better transit service because more frequency and coverage becomes practical. These differences suggest that congestion measures have limitations in cross-mode comparisons even when using common measures such as travel time. Mobility and accessibility measures address this limitation.

Definitions of Mobility and Accessibility

Congestion measurement entails quantifying both the adequacy and quality of transportation systems. Crucial aspects of adequacy are readily described using congestion measures couched in terms of deficiency and sufficiency. To describe quality, however, the complement of congestion needs to be quantified. This can be done in mobility or accessibility.

Mobility is the converse of congestion. Mobility is positive, and the ultimate in mobility is the ability to travel freely. The following definition is intended to reflect these concepts in a context useful for transportation system evaluation; thus it excludes such important externalities as access to auto ownership.

- *Mobility is the ability of people and goods to move quickly, easily and cheaply to where they are destined at a speed that represents free-flow or comparably high-quality conditions.*

If in application this definition is narrowed to focus solely on moving people and goods quickly, then mobility becomes a value measured in volume of people or goods and speed of movement. This is a concept applicable across all modes. When used in concert with a measure such as number of lanes or equivalent, it is a strong indicator of efficiency. A freeway with HOV lanes or rapid transit in the median will move more person-volume than a freeway without these treatments, and one hopes at a better or at least acceptable speed. The same variations that apply to the definition of congestion (location, time period, etc.) also apply to mobility.

Accessibility takes a different perspective to addressing quality. Whereas mobility refers to the ease with which people and goods can move or be moved about, accessibility refers to the ease with which desired activities can be reached from any or all locations (*4*). Accessibility is a broader measure than mobility in that it addresses land use and transportation system evaluation in combination.

Accessibility can have a variety of different definitions. The definition depends in part on whether local area accessibility or regional accessibility is the concern and on whether it is being used in connection with travel demand modeling or transportation network evaluation.

Local accessibility entails measures of land use mix, pedestrianization, and spatial separation within neighborhoods not directly applicable to congestion measurement. Accessibility as used in travel demand modeling necessarily employs formulaic elements difficult for decision makers to grasp.

More relevant to congestion measurement are regional accessibility and transportation network evaluation. Accessibility in this context is "a measure of the relative access of an area or zone to population, employment opportunities, community services, . . ." (*5*). Combining past practice of using travel time as the unit of spatial separation (*6*) with the acceptability approach used in defining congestion, the applicable definition of accessibility becomes

- *Accessibility is the achievement of travel objectives within time limits regarded as acceptable.*

This definition does not fully parallel the definition for congestion, in that it speaks of *absolute* travel times rather than time or delay *relative* to an observable benchmark, but it does adhere to the use of travel time relative to an acceptable value as the core concept. As in the case of acceptable congestion, acceptability will vary by trip purpose as well as by geographic location, time of day, and mode of travel.

Accessibility using this definition has two particular virtues. By using door-to-door travel time as the time measure, accessibility via alternative modes can be put on an essentially equal footing, as long as it is recognized that acceptability varies by mode. It is apparently as close to an ideal measure for multimodal performance analysis as can be achieved from the user perspective. In addition, it allows recognition that travel needs can be more easily satisfied not only if the transportation system is improved, but also if land use arrangements are rationalized or additional travel modes or options are made available to travelers. For example, accessibility to services can be enhanced either by improving transportation to and from services or by relocating services closer to residences and jobs. Thus, accessibility is a powerful concept that can be used to measure benefits accruing from the full range of multimodal improvements, mixed land use, balanced land use, and development density.

CONCLUSIONS

This overview of congestion measurement provides a framework within which to develop procedures to estimate congestion under various situations. It shows that congestion may take place along roadways, on transit facilities, or along sidewalks. This report, however, concentrates on roadway travel modes. The following sections of this report and the User's Guide provide information and procedures to collect and analyze congestion mobility and accessibility on freeways, tollways, and streets. The other uses, users, and audiences were studied to understand how roadway measures should be made compatible with requirements for other modes.

The preceding discussion centers on the needs for congestion measurement rather than available data. The recommended approach identifies the best measures of congestion and pursues a set of direct and surrogate data collection procedures to estimate those measures. Such a process provides a vision of congestion measurement that is compatible with current transportation data collection techniques, as well as those improvements expected in the next decade or two. It also recognizes the need to use historical and current data collection until those improvements can be realized.

CHAPTER 2

FINDINGS—REVIEW OF PRACTICE AND CONGESTION MEASURES

RESEARCH APPROACH—OVERVIEW OF THIS CHAPTER

The research for this study focused on meeting the needs for congestion and mobility measures. The initial approach included a survey of state Departments of Transportation, Metropolitan Planning Organizations, and other agencies involved in congestion measurement activities, and a comprehensive investigation of the literature. The survey and literature review formed the basis for evaluating congestion measurement needs, assessing the suitability of individual measurement techniques and selecting approaches to measuring congestion.

This chapter contains a summary of the congestion measurements that are being used, the needs for congestion measures, and the recommended analysis techniques to be used for quantifying congestion.

CONGESTION MEASUREMENT—REVIEW OF AGENCY PRACTICE

Numerous measures have been suggested or used over the last 60 years in an attempt to quantify traffic congestion. Several of these measures have been refined over time and today are incorporated into standard traffic analyses by state and local transportation agencies. Other measures of congestion have been used on a limited basis because of prohibitive data collection costs or a lack of understanding or acceptance among the measures' users and audiences. Still other congestion measures have been suggested in the literature by the research and academic community and remain untested and unutilized. This section contains a summary of the measures currently used by state and local agencies.

A "state of the practice" survey was distributed in 1992 to over 450 state departments of transportation (DOTs), metropolitan planning organizations (MPOs), congestion management agencies, and city traffic engineering departments to identify current agency practices for defining and measuring congestion. A detailed description of survey responses can be found in Appendix A of this project's Interim Report (*7*). The following sections provide a summary of survey responses.

Table 4 identifies users and target audiences. Table 5 identifies congestion measures actually used and those suggested for use. Level of service was the most frequently used measure by agencies; delay and travel times were the most frequently suggested measures.

Users and Uses

The "state of the practice" survey (*7*) identified the users and target audiences for congestion measures generated by each agency. The number of responses for each user group and audience is presented in Table 4. Inspection of the table reveals that transportation professionals are the most common users (as reported by 81 percent of the responding agencies) and target audience (77 percent) of congestion measures. Public policy makers also constituted a large percentage of users and target audiences.

Table 4 also reveals an interesting trend for nontechnical groups like the private sector and media. Although the private sector is a common user of congestion measures (48 percent), it is not considered a target audience by most public agencies (26 percent). The media are another group identified as a user of congestion measures (37 percent) but not a significant target audience (16 percent).

The responses in Table 4 indicate that although nontechnical groups are often the users of congestion measures, they are infrequently considered as target audiences for congestion measures. This implication provides a strong argument for the development of congestion measures that are simple and easy to understand for nontechnical audiences, yet rigorous and credible for technical groups.

Highway Capacity Manual Measures

Level of Service. The 1994 *Highway Capacity Manual* (HCM) currently serves as a standard for typical traffic engineering studies by most state and local agencies (*8*) just as the 1985 HCM (*8*) did when the survey was conducted. The 1994 HCM uses the level of service concept (LOS) to represent a range of operating conditions, and LOS ranges have been widely used as a basis for congestion measures. Approximately 90 percent of all agencies (Table 5) responding to the survey incorporate the LOS concept as a measure of congestion; however, there is no consensus among agencies regarding the LOS range corresponding to the threshold, or beginning, of congestion. Of the agencies

TABLE 4 Summary of survey responses—users and target audiences of congestion measures

Group	Agency Responses to Question Regarding:[a]	
	Users	Target Audiences
Transportation professionals	83 (81%)	79 (77%)
Public policy makers	75 (74%)	71 (70%)
Private sector (developers, etc.)	49 (48%)	27 (26%)
Land use planners	46 (45%)	37 (36%)
Media	38 (37%)	16 (16%)
General public	36 (35%)	28 (27%)

Source: Reference (7).
[a] Multiple responses by each agency were permitted.
83 - Number of responses from surveyed agencies.
81% - Percent of responses.

using LOS as a measure of congestion, 45 percent define LOS D or worse as congestion, whereas 20 percent and 14 percent define LOS C and LOS E or worse, respectively. An acceptable standard for LOS has not been defined, but it could be based on design guidelines for the specific type of facility (*9*). Approximately 13 percent of the responding agencies using LOS have defined standards based on functional classification (e.g., freeway versus arterial street) or location of facility (e.g., urban versus rural). An acceptable standard for LOS could also be the result of a public review

TABLE 5 Summary of survey responses of congestion measures used and suggested by agencies

Measure	Number of Agencies Using Measure[a]	Suggesting Measure for Use[a]
Level of Service	82 (90%)	4 (9%)
Delay	17 (19%)	14 (31%)
v/c ratio	15 (16%)	2 (4%)
Travel time/speed	12 (13%)	11 (24%)
Traffic volumes	4 (4%)	0 (0%)
Capacity	2 (2%)	0 (0%)
Density	2 (2%)	4 (9%)
Lane occupancy	2 (2%)	0 (0%)
Vehicle-hours of travel	2 (2%)	2 (4%)
Vehicle occupancy	2 (2%)	0 (0%)
Queue duration	1 (1%)	1 (2%)
Queue length	0 (0%)	2 (4%)
Accident rate	1 (1%)	2 (4%)
Duration of peak period	1 (1%)	1 (2%)
Failing signal cycles	1 (1%)	0 (0%)
Vehicle emissions	0 (0%)	3 (7%)
Vehicle-miles of travel	0 (0%)	5 (11%)

Source: Reference (7).
[a] Different response rate for each survey question; multiple responses by each agency were permitted.
82 - Number of responses from surveyed agencies.
90% - Percent of responses.

and comment process to identify goals and objectives for the community.

Freeway Analyses—Density and Volume-to-Capacity (v/c) Ratio. The LOS for a basic segment of freeway or other uninterrupted flow facility is defined by the vehicular density (passenger cars per mile per lane). Only two of the responding agencies (2 percent) use density as a measure of congestion; additionally, only 9 percent of the responding agencies suggested vehicular density (using aerial photography) as an appropriate measure of congestion. Because the 1994 HCM presents a calibrated relationship between the v/c ratio and density, the v/c ratio is frequently used in LOS analyses in lieu of density because of the relative ease of traffic volume data collection (relative to also measuring speeds to establish densities directly). Approximately 16 percent of the responding agencies use the v/c ratio as a surrogate measure of congestion, but only 4 percent of the agencies suggested the v/c ratio as an appropriate congestion measure. As with LOS ranges, there is no consensus on the v/c ratio corresponding to the threshold of congestion. Of the responding agencies using the v/c ratio as a measure of congestion, 36 percent, 45 percent, and 19 percent defined the congestion threshold value as a v/c ratio equal to or greater than 0.8, 1.0, and 1.25, respectively.

Signalized Intersection Analyses—Average Delay per Vehicle. The LOS for signalized intersections is defined in the surrogate measure, average stopped delay per vehicle. Although signalized intersections are often the source of congestion along arterial streets, only 10 percent of all LOS analyses by responding agencies included signalized intersections. Most of the LOS analyses concentrated on all functional classes (42 percent), freeways or expressways (18 percent), and principal arterial streets (14 percent).

Capacity. The capacity of a roadway facility is used by two agencies (2 percent), both state DOTs, as a relative measure of congestion. Roadway capacities are estimated using methodologies in the 1994 HCM (*8*). None of the responding agencies suggested roadway capacity as an appropriate congestion measure.

Queuing-Related Measures

Queue Length and Duration. Although no responding agencies used queue length, two of the agencies (4 percent) suggested it as an appropriate measure of congestion. The duration of a queue (i.e., time of congestion) is used by one agency and was suggested by another agency as an appropriate measure of congestion. Queue length and duration can be determined by direct observation, and key parameters like maximum and average number of vehicles in the queue can be computed. State and local DOTs and MPOs have contracted a consulting firm (Skycomp, Inc.) that uses aerial photography techniques to determine queue length and duration on entire roadway systems, toll plazas, and other isolated capacity constrained locations (*10*). Several computer traffic models produce estimates of queue length or queue duration, but these models are sensitive to assumptions about capacity.

Lane Occupancy. The lane occupancy, a spot measurement of density that is typically reported as the percentage of time a travel lane is occupied by traffic, is used as a measure of congestion by two of the responding agencies (2 percent). Both of these agencies are state DOTs in states with several medium to large urban areas. In both cases, the lane occupancy measurements are gathered from vehicle detectors in the pavement that are part of many freeway surveillance and control systems. Lane occupancy was not suggested as an appropriate measure by any of the responding agencies and was not used or suggested as a measure of congestion by any of the MPOs.

The Illinois Department of Transportation incorporates lane occupancy measurements on Chicago area freeways into a measure of minute-miles of congestion (*11,12*). The measure is defined as the product of congested miles and congestion duration on individual freeway segments. The detector stations are located in the center lane at half-mile spacings. The threshold for congestion at each station is based on a 30 percent occupancy for a 5-min period.

Travel Time Measures

The collection of travel time data is a component of standard traffic engineering studies; however, limited financial resources and higher priorities often prevent the collection of travel time data except in the case of specific improvements. Travel time studies are conducted by 16 of the responding agencies (18 percent); however, travel time or speed measures are used by only 12 of these agencies, 11 of whose jurisdictions include medium- to large-size urban areas. A slightly higher percentage of responding state DOTs (15 percent) use travel time or speed measures than responding MPOs (10 percent). The studies are primarily conducted on freeways (46 percent) and principal arterial streets (26 percent).

Travel Speed. Several measures can be calculated from the data typically collected by travel time studies. The level of service for the different classes of arterial streets is defined by the average travel speed, but only 17 percent of those agencies conducting travel time studies use travel speeds for determining arterial street LOS. Most travel time studies compare average travel or running speeds to a base year or "before" condition; in this case, approximately 83 percent of the responding agencies use a base year comparison for their travel speeds.

Although only 13 percent of the responding agencies conduct travel time studies, 24 percent suggested the use of travel time or speed as an appropriate congestion measure. The most commonly cited reason for not using these measures was inadequate staffing and budget (56 percent of responding agencies). Those agencies suggesting travel time measures were evenly split between small, medium, and large-size urban areas, with slightly more MPOs suggesting the use of travel time measures.

The Greater Houston Chamber of Commerce has used several key indicators of congestion to document the progress of Houston's transportation system over the past years (*13*). Peak direction and peak-hour travel speeds for all freeways in the urban area and for the six major radial freeways were used as two such indicators. Average peak period travel times between several major residential and employment centers were presented in a matrix format to illustrate significant improvements in mobility.

The Metropolitan Washington Council of Governments at one time developed a "User Satisfaction" transportation system performance measure based on acceptable travel time and delay (*14*). The measure more recently was refined to address separately single drivers, drivers with passengers, auto passengers, and transit users (*15,16*). The measure incorporated a set of curves that show the percent of users satisfied for a given trip length and time.

Delay. Vehicular delay is often calculated by comparing actual travel speeds to desired travel speeds (e.g., free-flow speeds). Delay is the second most commonly used measure (next to LOS) among those agencies using congestion measures (19 percent of responding agencies). Many agencies did not explicitly report the methodology used to calculate delay, but it is assumed that, in most instances, delay is calculated as the difference in average travel speeds and "acceptable or desired" speeds.

Delay also could be estimated with a traffic modeling methodology if certain input values are known, as with the 1994 HCM signalized intersection analysis. Delay measures most often were applied to all functional classes (49 percent of responding agencies) daily (34 percent) or by peak hour (26 percent). There was no significant difference in the percentage of responding state DOTs and MPOs using delay measures. The use of delay measures among MPOs was fairly consistent among the small, medium, and large-size urban areas, while only state DOTs with medium and large-size urban areas reported the use of delay measures.

Delay was the measure most frequently suggested as an appropriate measurement of congestion (31 percent of responding agencies). Like the use of travel time measures, only state DOTs with medium and large-size urban areas suggested delay measures as appropriate. There was not a significant difference between the percentage of responding state DOTs (40 percent) and MPOs (32 percent) suggesting delay as an appropriate measure of congestion. Besides base year comparisons, determination of arterial street LOS and estimation of delay, no other congestion measure that utilized travel time studies was reported.

Surrogate Measures

Surrogate measures of congestion are those used to indirectly quantify congestion when resources are not available to conduct specific congestion studies, or when the prediction of future congestion trends is of interest. A typical example of surrogate measures include those used in the calculation of LOS in HCM analyses, like the volume-to-capacity (v/c) ratio for freeways or average stopped delay per vehicle for signalized intersections or average travel speed for arterials. In these cases, traffic flow and roadway characteristics are used to predict LOS which, in turn, becomes a surrogate for congestion assessment. Planning agencies use surrogate measures to estimate speeds for traffic assignments.

Besides the HCM-related measures previously discussed, no surrogate measures were used by the responding agencies on a consistent basis. The most commonly reported surrogate measure was traffic volumes (typically the average daily traffic [ADT] volume), with only four of the responding agencies (4 percent) reporting its use. No agencies offered traffic volumes as an appropriate congestion measure. A measure related to ADT is vehicle-miles of travel (VMT), defined as the product of ADT and section length for a given segment of roadway. At least five responding agencies (9 percent) suggested VMT or some VMT measure as an appropriate measure of congestion. Most of these agencies were state departments of transportation that have easy access to traffic volume counts from permanent automatic traffic recorders or other volume counting programs, like the Highway Performance Monitoring System.

Vehicle-hours of travel was reported as a measure of congestion by two agencies (2 percent), and was suggested as an appropriate measure by another two agencies. Vehicle occupancy (persons per vehicle) is used by two agencies (2 percent of those responding), but was not suggested by any agency as an appropriate measure of congestion. The number of accidents is used by a single agency, but was suggested by another two agencies as an appropriate congestion measure. Other surrogate measures reported by a single agency include the duration of the peak period and the number of failing signal cycles.

Treatment of Different Vehicle Types

The negative effects of heavy vehicles on the quality of traffic flow have been well documented in the literature. The survey responses, however, indicate that most state and local agencies do not account for the effects of different vehicle types on their congestion measures. Approximately 77 percent of the responding agencies reported that they do not treat different vehicle types separately in their congestion measures. Of the 23 percent that do treat different vehicle types separately, 95 percent use the passenger car equivalency concept contained in the 1994 HCM. The remaining agency (5 percent) differentiates between the different modes (e.g., single drivers, HOV, or transit) in its congestion measures.

Recent Advances in Data Collection

Current and developing technologies, particularly in the intelligent transportation system (ITS) area, could significantly lessen the cost and difficulty of collecting travel time information. Several urban areas, like Chicago and Houston, have implemented programs where participating motorists act as traffic stream "probes" and report their location at various points along their trip with personal cellular phones or via electronic tags and detectors. These motorists' reports are typically compiled and analyzed in a traffic information center in an attempt to provide real-time travel information.

The ADVANCE project, an ITS operational test in the suburbs of Chicago, uses 75 "probe" vehicles for the collection of travel time information via in-vehicle navigation and information systems (*17*). A system of electronic tag readers has been placed on several freeways in Houston to record travel time by motorists who have tags for toll purposes or who have been given tags to participate in the study (*18*). The information is collected and displayed in real time.

CONGESTION MEASUREMENT—REVIEW OF THE LITERATURE

Many measures of congestion have been proposed or examined in the literature. Most of these measures have not been used on as wide a scale as those measures discussed earlier and have not been adopted for use by most state or local transportation agencies. The congestion measures discussed below were identified in the literature review, and the reader is encouraged to refer to Appendix B of this project's Interim Report (*7*) for a more extensive discussion.

Empirical Relationships

Several of the early efforts in congestion measurement centered on empirical relationships that attempted to incorporate driver effort and satisfaction into an index of the quality of traffic flow. Greenshields' number was equal to the product of speed and direction changes over a section of roadway, and served as an indicator of the "traffic roughness" of roadway sections (*19*). The quality of traffic transmission index (Q index) was defined as a function of average speed and the number and sum of speed changes (Equation 1) (*20*).

$$Q = \frac{KS}{\Delta_s \sqrt{f}} \tag{1}$$

where

Q = quality of traffic transmission index,
K = 1,000 (constant),
S = average speed (mph),
Δ_s = absolute of speed changes per mile, and
f = number of speed changes per mile.

The level of traffic service index was directly measured using a "driveometer" and included estimates of driver annoyance due to delay, a ratio of satisfaction versus effort expended, and a quality factor (*21,22*). These indices required data that were both difficult and expensive to collect, and the index values were difficult to comprehend.

Highway Capacity Manual Measures

Volume-to-Capacity Ratio. Because of its relative ease of collection and widespread acceptance by most transportation agencies, the v/c ratio has been incorporated into several measures of congestion. One widely reported measure in the literature is the percentage of congested freeway lane-miles (based on the v/c ratio for the peak hour) (*23,24,25,26,27,28,29,30*). A similar measure is the percentage of vehicle-miles of travel occurring in peak hour congested conditions, with congested conditions defined by the v/c ratio (*26,27,28,29,31,32,33,34,35,36*). Other HCM-related measures suggested to account for the duration of congestion are the number of 15-minute periods, or the vehicle-hours of travel (VHT), above a specified LOS congestion threshold.

The measures of effectiveness for levels of service as defined in the 1994 HCM are summarized in Table 6. Density, or the vehicles per lane per mile, is the basic measure for freeways and multilane highways. Average travel speed is the basic measure for arterials, whereas average stopped delay is the measure for signalized intersections. Percent time delay is the basic measure for two-lane highways.

Service levels range from A through F with service level A the best and service level F, failure. Congestion normally is associated with service levels D, E, and F. Criteria for service levels vary by type of facility.

K Factor. Another HCM-related measure suggested as an indicator of congestion is the systemwide freeway K factor, where the K factor is the percentage of average annual daily traffic occurring in the peak hour (*23*). As traffic congestion levels rise, travelers move their trips to hours other than the peak hour, and the K factor decreases. A systemwide freeway K factor less than 9.2 has been suggested to indicate undesirable levels of congestion.

Queuing-Related Measures

Queue Length and Duration. The Skycomp Corporation (*10*) specializes in aerial data acquisition and regularly conducts congestion surveys of toll facilities in the New York metropolitan area. Measures like queue length, queue volume, and other delay measures are calculated using aerial photo logs and are commonly reported for isolated capacity restrictions like toll plazas and bridges. Density and LOS measures also are estimated from aerial photos or by experienced observers.

Lane Occupancy. Lane occupancy measurements are collected by two of the state DOTs that have freeway surveillance and control systems, and have been incorporated

TABLE 6 Measures of effectiveness for level of service definition—1994 Highway Capacity Manual

Type of Facility	Measure of Effectiveness
Freeways	
Basic freeway segments	Density (pc/mi/ln)
Weaving areas	Average travel speed (mph)
Ramp junctions	Flow rates (pcph)
Multilane Highways	Density (pc/mi/ln)
	Free-flow speed (mph)
Two-Lane Highways	Percent time delay
Signalized Intersections	Average individual stopped delay (sec/veh)
Unsignalized Intersections	Average total delay (sec/veh)
Arterials	Average travel speed (mph)
Transit	Load factor (pers/seat, veh/hr, people/hr)
Pedestrians	Space (sq ft/ped)

Source: Reference (8).

Note: pc/mi/ln—passenger cars per mile per lane
pcph—passenger cars per hour
sec/veh—seconds per vehicle
pers/seat—persons per seat
veh/hr—vehicles per hour
people/hr—people per hour
sq ft/ped—square feet per pedestrian

into several other congestion measures. The percent occupancy is equal to the vehicles per mile times the average length of the vehicle divided by 5,280. In the 1950s, Rothrock and Keefer defined a congestion index as the ratio of the actual time-of-occupancy to the optimum time-of-occupancy (*37*). In their definition, the optimum time-of-occupancy was based on local conditions like speed limits and time of day.

Polus and Schofer defined a reliability index (R index) based on median lane occupancy measurements and the number of lanes (*38*). The R index was based on the premise that flow reliability, and consequently quality of traffic service, is inversely related to the variance of the distribution of median occupancies over a period of time. In his thesis, Benke uses lane occupancy rates for Minneapolis freeway segments to assign traffic condition grades (e.g., "A" through "D" and "F") on driver information signs (*39*).

Travel Time Measures

Early Studies. The use of travel time studies and related measures to describe system performance and congestion permeated the traffic engineering literature as early as the late 1920s. The early studies concentrated on determining average travel speeds in congested downtown areas and attempted to locate the magnitude and sources of travel delay. A 1950 study of traffic conditions in Chicago's central business district reported that traffic delays accounted for time losses of 2 minutes per trip for auto drivers and 2½ minutes per trip for transit passengers across the area (*40*).

Early research derived sampling sizes for travel time studies and presented relationships between travel speed and traffic volume, density, traffic signals, and other roadway characteristics (*41,42*). A paper by Coleman found a correlation between travel times (in minutes per mile) and signal density when stratified by peak-hour v/c ratios for flows less than the critical density (Figure 2) (*43*). A later report illustrated hypothesized relationships between average speed and v/c ratio for arterial streets (Figure 3) (*44*).

The National Committee on Urban Transportation, now defunct, suggested travel speed standards for different functional classifications (Table 7), and also minimum desirable travel times for trips of various lengths (*45,46,47*).

Speed Measures. The literature has suggested several speed measures besides average travel speed. The average travel rate, in minutes per mile, is the reciprocal of average travel speed (*48,49*). Peak period nominal speeds are a weighted average of speeds on freeways and principal arterial streets, which allow comparison of the freeway and principal arterial street network between urban areas. The ratio of peak period to off-peak period speed, and the average travel time per trip and per peak period trip, are also suggested as direct measures of congestion. Variance of speed, or acceleration "noise," provides a measure of the dispersion or change of speeds.

Speed-flow relationships have been used in making peak hour "capacity restrained" traffic assignments for more than three decades (Table 8). The original Bureau of Public Roads Curve was based on the following formula:

$$S = \frac{S_0}{1 + a\left(\frac{v}{c_1}\right)^b} \tag{2}$$

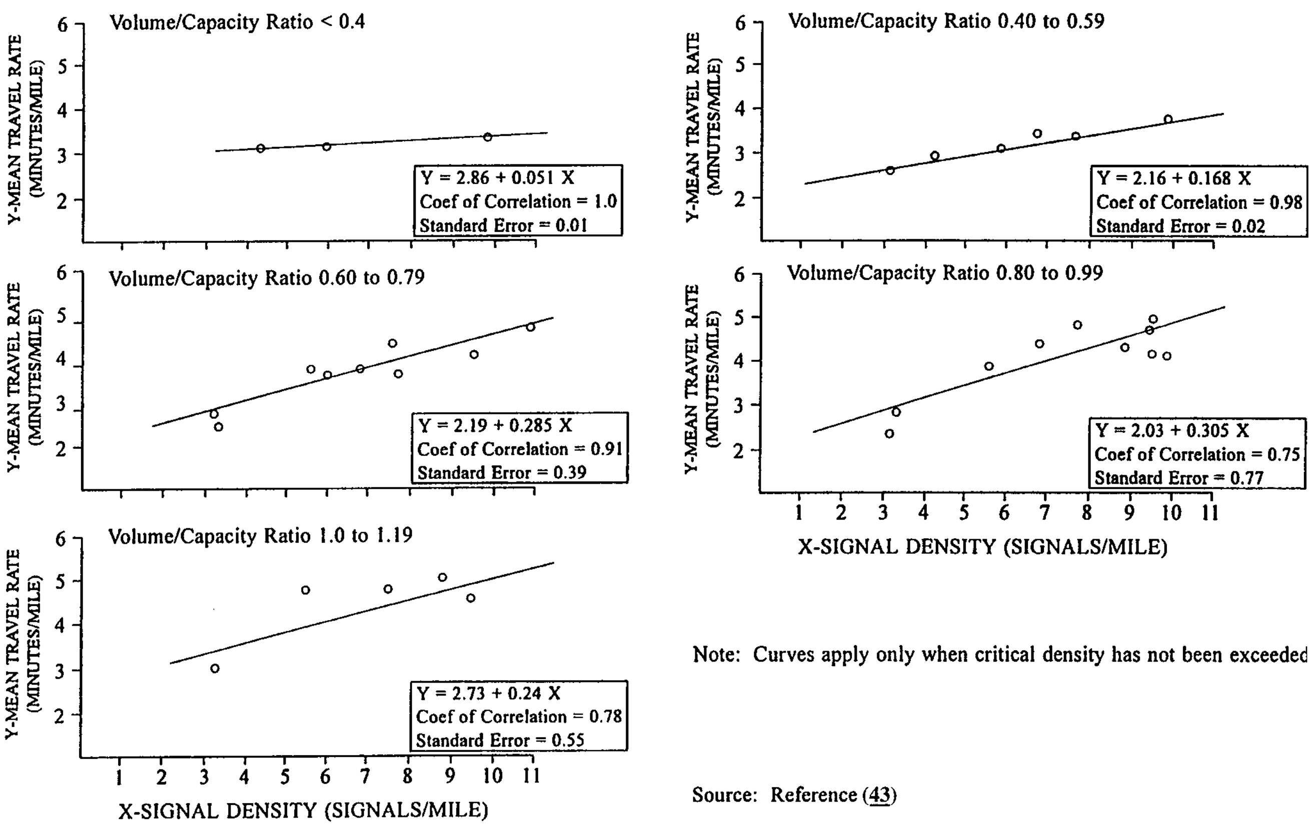


Figure 2. Relationship between travel time and signal delay.

where

S_0 = free-flow travel speed;
S = travel speed at volume v; and
c_1 = practical capacity $\cong$ 80% of maximum capacity, c_2.

The values of a and b were 0.15 and 4, respectively. Several communities have modified these coefficients or have sometimes changed the basic formulation. Dowling et al. (*50*) have suggested enhanced curves based on the maximum capacity (C_2) that have a value of 10 for b. Values of a are 0.05 for freeways and 0.20 for arterials.

Delay Measures. Delay measures incorporating travel time data typically compare the average travel speed to some desirable (e.g., off-peak or free-flow) travel speed. In this manner, only recurring congestion is incorporated into the delay measure. Several research efforts that developed delay measures also incorporated a methodology to estimate the nonrecurring delay (*25,26,27,28,32,33,34, 35,36,51*).

The delay rate, in minutes per mile, represents the difference between the actual travel rate and a standard travel rate. Similarly, the relative delay rate (R) is defined as the delay rate divided by the standard travel rate (Equation 3).

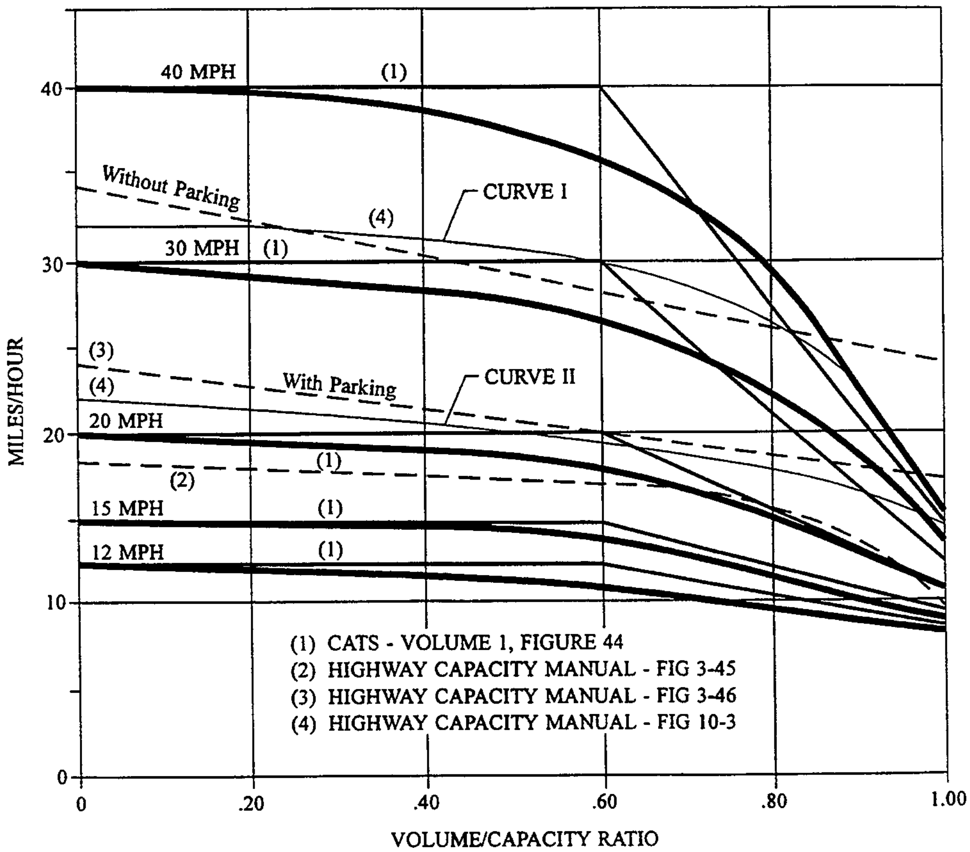
$$R = \frac{t_1 - t_2}{t_2} = \frac{t_1}{t_2} - 1 \qquad (3)$$

where

R = relative delay rate,
$t_1 - t_2$ = delay rate (minutes per mile),
t_1 = actual travel rate (minutes per mile), and
t_2 = standard rate (minutes per mile).

Values of delay may be normalized by various factors to produce more meaningful measures of congestion and allow an unbiased comparison between areas. These normalizing factors include per vehicle, per vehicle-miles of travel, per capita, per person delayed, per commuter, per trip, and per lane-mile. The delay ratio, or ratio of delay time to overall travel time, has also been suggested.

Time Measures. Travel time measures, unlike speed measures, can be aggregated more easily and are more amenable to statistical analysis. For example, the average delay rate for an individual roadway, urban area, or region may be calculated using travel times (in minutes per mile) for each roadway segment (Equation 4), and weighted by the section length and/or volume.



Note: Heavy lines show suggested curves.
Source: Reference (44)

Figure 3. Speed and volume/capacity ratios—arterial streets.

$$\bar{\Delta}_t = \frac{\sum (t_1 - t_2)_i M_i V_i}{\sum M_i V_i} \qquad (4)$$

where

$\bar{\Delta}_t$ = average delay per vehicle per mile,
M_i = length of section i (miles),
V_i = traffic volumes on section i, and
$(t_1 - t_2)_i$ = delay rate.

A modified travel time is equal to the total travel time divided by the time the vehicle is in motion, multiplied by the total travel time (Equation 5). Modified travel times are effectively weighted by the amount of time stopped.

$$t_{modified} = \left(\frac{t_{total}}{t_{running}}\right) \times t_{total} \qquad (5)$$

Travel time contour maps, or isochronal (lines of equal travel time) maps, have been used to illustrate travel times

TABLE 7 Peak-hour urban travel standards suggested by National Committee on Urban Transportation

Functional Classification	Travel Speed (mph)	Travel Rate (minutes per mile)
Expressway-Freeway	35	1.71
Major Arterial	25	2.40
Collector	20	3.00
Local Streets	10	6.00

Source: Reference (45).

TABLE 8 Speed-flow curves reported in the literature

$$S = \frac{S_o}{1 + a\left(\frac{v}{c}\right)^b}$$

where

S_o = free flow travel speed
S = travel speed at volume v
c = capacity
c_2 = maximum capacity
c_1 = practical capacity ≈ .80 maximum capacity

Source of Curve	Value Used in Formula			
	c	a	b	Remarks
1. BPR	c_1	.015	4	
2. BPR	c_2	0.366	4	
3. Phoenix Freeways	c_1	0.1225	8	$v/c_1 < 1.33$[1]
4. Phoenix Arterials	c_1	0.1513	7	$v/c_1 < 1.33$[2]
5. San Francisco	c_2	0.45	4	
6. Detroit	c_1	0.15	4	$v/c \leq 1.85$[3]
7. Dallas				[4]
8. Dowling Freeways Arterials	c_2 c_2	0.05 0.20	10 10	

[1] For values over 1.33
$S = S_o\,[0.25 + 0.4374\,(\frac{v}{c})^{-3}]$

[2] For values over 1.33
$S = S_o\,[0.25 + .5184\,(\frac{v}{c})^{-3}]$

[3] For values over 1.85
$S = \frac{S_o}{2.85}$

[4] $S = \frac{S_o}{1 + 0.015e^{b(\frac{v}{c_1})}}$

where b = 4.0 for daily travel
6.0 for peak hour travel

Source: Reference (50).

from a CBD to outlying areas (Figure 4). The difference between peak-hour and off-peak travel time from the CBD, or other major activity center, provides an overall picture of the travel time (or distance) losses resulting from congestion (Figure 4). Travel time contours have also been done in successive years to indicate the congestion trends.

Congestion Indices

There have been several attempts to develop indices of congestion that quantify traffic problems on an areawide basis. These indices provide relative estimates of average conditions, and may be compared between urban areas or over time. In most cases, these indices have been used for policy or planning-level analyses.

Individual and Societal Congestion Indices. These individual and societal congestion indices, both of which have a commuter and noncommuter version, were empirical relationships developed to incorporate elements of congestion important to different transportation system users (*52*). Each of the four indices included an indicator of peak-period traffic quality using readily available data. The study was one of the first to recognize the need for several measures to describe the different elements of congestion and their relation to system users' perceptions.

Congestion Severity Index. The congestion severity index (CSI), a measure of freeway delay per million vehicle-miles of travel (VMT) (Equation 6), used the Highway Performance Monitoring System (HPMS) to estimate relative congestion levels for 37 large U.S. urban areas (*25,53,54*). The CSI methodology developed by Lindley used 1985 HCM calculations and local freeway traffic distributions to estimate recurring delay, while nonrecurring delay was estimated by using an assumed distribution of incidents (based on VMT) and an incident model developed earlier (*55*). The

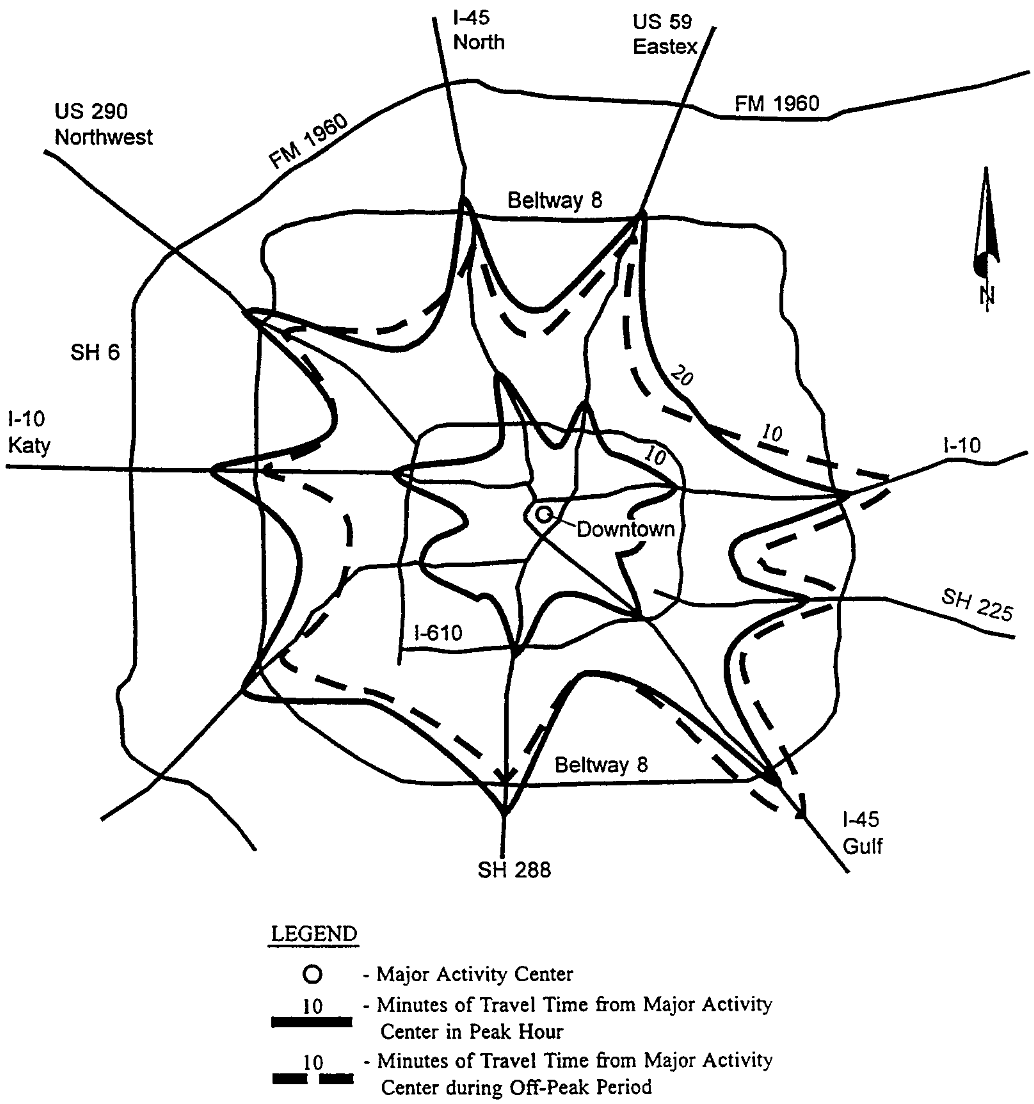


Figure 4. Example of isochronal travel time map.

analysis assumed the threshold of congestion to begin at a v/c ratio of 0.77 or greater (LOS D or worse). A modified version of the CSI was later reported that included arterial street delay per million VMT (*30*).

$$CSI = \left(\frac{Total\ Freeway\ Delay\ (veh.\text{-}hrs.)}{Freeway\ VMT\ (million)} \right) \tag{6}$$

Roadway Congestion Index. The roadway congestion index (RCI), a measure of the daily VMT per lane-mile of freeways and principal arterial streets, is an empirically derived formula that uses HPMS data to quantify the relative congestion levels in urban areas (*23,24,26,27,28,32,33,34,35,36*). The RCI equation weights the daily VMT per lane-mile values for the two functional classes by its respective amount of daily VMT, which is then normalized by values representing the threshold of congestion (LOS D or worse) (Equation 7). Once normalized, RCI values greater than 1.0 represent undesirable levels of roadway congestion within an area. The basic assumption is that congestion begins when the areawide average ADT per lane reaches a given threshold.

Lane-Mile Duration Index. The freeway lane-mile duration index ($LMDI_F$), a measure of the extent and duration of freeway congestion, was developed by Cottrell in a study of con-

$$RCI = \frac{[Freeway\ DVMT/Ln.\text{-}Mi. \times Fwy.\ DVMT] + [Prin.\ Art.\ DVMT/Ln.\text{-}Mi. \times Prin.\ Art.\ DVMT]}{[13{,}000 \times Fwy.\ DVMT] + [5{,}000 \times Prin.\ Art.\ DVMT]} \tag{7}$$

gestion in 35 urban areas (*56*). The $LMDI_F$ value for each urban area is the sum of the product of congested freeway lane-miles and congestion duration (hours) for individual roadway segments (Equation 8), and is calculated using the indicator of average annual daily traffic volume per hourly capacity (AADT/C). The methodology assumed a v/c ratio greater than 1.0 (LOS F), or AADT/C ratio greater than 9.0, to represent congested travel conditions. The study found this threshold of congestion to be consistent with the public's tolerance and current practice of the California Department of Transportation.

$$LMDI_F = \sum_{i=1}^{m} \begin{bmatrix} Congested & Congestion \\ Lane\text{-}Miles_i \times & Duration_i(hours) \end{bmatrix} \qquad (8)$$

where i equals an individual freeway segment, and m equals the total number of freeway segments in an urban area.

Other Indices. Several other indices have been developed in an attempt to measure the person-carrying capacity of corridors (*57,58*). The speed of person volume is the product of travel speed and peak-hour person volume per lane. A person movement index, or rate of person movement, has been defined as the product of peak-hour vehicle occupancy and travel speed. The study developed a corridor mobility index (CMI) for freeways, high-speed HOV lanes, and rail transit, and another for arterial streets and arterial HOV lanes. The CMI equation used the speed of person volume concept and developed values to normalize the equation elements. A correlate is the concept of productive capacity—which is the product of capacity and speed.

Summary

A "state of the practice" congestion measurement survey and literature review was used to identify over 30 distinct congestion measures that are currently used by state and local agencies, have been used on a limited basis by various organizations, or have been proposed or examined in the literature. As can be expected, there were many differences between current agency measures and measures contained in the literature. The differences are attributable mainly to the cost of data collection, the credibility and simplicity of the measures, and the ability to forecast future conditions.

Most state and local agencies using congestion measures employ the level of service (LOS) concept as presented in the 1994 HCM. Because the LOS is defined in surrogate measures like the v/c ratio, traffic volume counts, roadway characteristics, and traffic signal timing are essentially all that is needed to "measure" congestion. The LOS measure ranges from "A" (best service) to "F" (worst service), a simple concept analogous to school letter grades and comprehensible by most nontechnical audiences.

Despite the extensive reported use of LOS measures, only a few agencies judged the LOS concept to be the preferred measure. Many of the agencies thought delay to be a more appropriate measure of congestion. Delay, typically calculated by comparing average travel speeds to "desirable" speeds, was the second most commonly used measure, and one that most people can easily relate to. Travel time studies were used by approximately one-fifth of all responding agencies to determine average travel speeds and delays. The most common reason cited for not using this or other preferred measures was inadequate staffing and budgetary constraints.

The v/c ratio has been incorporated into several measures of congestion because of its widespread acceptance by most transportation agencies. Recent efforts in quantifying congestion on an areawide basis have resulted in the development of several congestion indices. These indices use available traffic volume data but require complex calculations and are somewhat difficult to comprehend. There were several other measures, with most used by only a few agencies or inconsistently.

The literature contained a wider assortment of congestion measures than those used by state and local agencies. The measures cited earliest and most consistently throughout the literature were travel time measures, typically average speed or delay. Travel time studies were conducted over 60 years ago to measure system performance and to determine locations of delay. Numerous speed and delay measures can be calculated with travel time data. Recent advances promise to lower the cost and difficulty of collecting travel time data significantly.

EVALUATING CONGESTION MEASURES

The many ways of measuring congestion developed over the years have been joined by additional measures and indices defined and/or formulated as part of this research project. While some of these measures are simple to comprehend and apply, others are complex.

In light of the wide range and diversity of available measures, it is important to provide and use a systematic basis for assessing and comparing congestion measures. Such an evaluation makes it possible to identify and separate measures that are useful in one or more of the user/uses/audience combinations from measures that are either less useful or inappropriate for certain analyses. As already identified, some measures may be useful in some instances and inappropriate in others. It is important that every use of congestion measures be assessed in such a systematic process. This evaluation provides a framework for such a process and identifies measurements relevant to most common congestion analyses.

The "Ideal" Congestion Measure

The analysis of the uses and users of congestion (outlined previously) indicates that the "ideal" congestion measure would (1) be easy to understand; (2) clearly define congestion (i.e., be unambiguous); (3) be accurate and consistent in its description; (4) be able to describe existing conditions *and* assess future conditions; (5) be able to reflect different geographic settings, time frames, and levels of detail; (6) be applicable to different urban travel modes (both individually and simultaneously); and (7) be relatively inexpensive and easy to collect.

Evaluation Criteria

Evaluation criteria were based on the "ideal" congestion measure characteristics. The measures that can be used over the widest range of conditions were identified using those criteria. This does not mean that the measures that rank low in this evaluation are not appropriate for any analysis; indeed, several are very useful, but only in more limited circumstances than the highly ranked techniques. These criteria are summarized in Table 9 and can be grouped into the following basic categories:

- *Clarity and simplicity*—understandable, unambiguous, and credible.
- *Descriptive and predictive ability*—ability to describe existing conditions, predict change, and be forecast.
- *Analysis capability*—ability to apply statistical techniques (e.g., sampling and regression) to provide a reasonable portrayal of congestion and replicability of results with a minimum of data collection requirements.
- *General applicability*—applicability to various modes, facilities, time periods, and scales of application.

In addition to serving as general guidelines for evaluating prospective congestion measures, these criteria provide the basis for a "fatal flaw analysis" whereby critical problems associated with certain measures for certain purposes can be identified and such measures can be excluded for particular uses.

Comparative Evaluation

To conduct a comparative evaluation, the various congestion measures presented in the previous section of this report, as well as additional measures from the literature along with measures developed as part of this project, were grouped into the general categories of

- Early empirical concepts;
- Highway Capacity Manual (HCM) and HCM-related concepts;

TABLE 9 Evaluation criteria

General Category	Specific Criteria Included Within Respective Categories
Clarity and simplicity	• Simplicity - easy to understand - easy to apply/analyze/interpret - easy to communicate • Unambiguous • Professional credibility
Descriptive and predictive ability	• Describes and assesses existing conditions/identifies problems • Predicts change and can be used for forecasting purposes • Tests options and opportunities - traffic controls/operations - system redesign/expansion - traffic growth, development impacts - highway performance monitoring - congestion management programs - policy actions • Reflects changes in traffic flow (i.e., flow dependency)
Analysis capability	• Economical data requirements - minimizes data requirements - uses readily available data - minimizes data collection costs • Conducive to statistical analysis - allows data aggregations - produces straightforward variance estimates - permits sampling procedures • Achieves consistent results • Provides reasonable representation of congestion/mobility
General applicability	• Applies to various transportation modes (individually and in multi-modal scenarios) • Reflects facility type (freeway, arterial, etc.) • Reflects time duration of congestion • Reflects geographic extent of congestion (propagation) • Adapts to varying scales of application and geographic settings (location, route, corridor, etc.) • Reflects varying degrees of congestion (large and small cities) • Correlates with air quality and energy impacts

- Lane occupancy rates and queues;
- Travel time measures;
- Miscellaneous measures (e.g., headway distributions); and
- Traffic flow per effective lane measures and congestion indices.

These basic types of measures are compared in Table 10. The comparison is based on the general criteria outlined in Table 9. Key considerations are outlined for each type of measure in the following discussion. Appendix C of the Interim Report (*7*) includes a more complete description of the measures discussed.

Early Empirical Concepts. Empirical measures developed during early attempts to quantify congestion (as Greenshields' Quality of Transmission Index) are generally difficult to visualize and comprehend. The typical complexity of these measures requires intensive data collection and complicates any statistical analyses. While most of these measures can be used to describe existing conditions, none of the measures can predict change or be used for forecasting purposes.

Early empirical measures also relate specifically to automobiles and trucks; thus, they lack applicability to several other modes of travel. The characteristics typically associated with these measures lead to difficulty in interpretation and, therefore, poor credibility among practitioners.

Highway Capacity Manual Measures. Unlike the early empirical measures, HCM measures are easy to understand. As a result, the measures are commonly applied in practice and have credibility among the professional community. The measures can be used to analyze existing conditions and assess future operations for roadways.

HCM-related measures require detailed, site- or location-specific input data and, in some instances, the application of complex models. These measures are, therefore, well-suited to analyze intersection or short roadway section problems or operations. Because of the detailed information required and the complexity of certain procedures, however, HCM measures are not well suited for policy or large-scale planning analyses. Corridor analyses are also difficult with the HCM procedures; the process involves combining the results of several individual intersection analyses to simulate actual performance.

HCM procedures are often discarded by agencies doing corridor or system level analyses because of the data and computational requirements. Techniques developed from empirical analyses with less supporting information than HCM often are applied instead. As noted in previous sections, HCM analysis procedures are not well suited to multimodal comparisons.

The ability of HCM-related measures to quantify congestion accurately depends upon the validity of the relationship between volume-to-capacity ratios and delay and, in the case of signalized intersections, the accuracy of the stopped delay equations (especially under severely congested conditions). This relationship has changed in the numerous revisions of the HCM (1956, 1965, 1985, and 1994), causing different assessments of similar traffic conditions.

Direct travel time measures are consistent in regard to their evaluation of traffic conditions. Because delays and travel times in the HCM-related procedures are not the results of direct observations, these measures cannot be considered direct measures of congestion. Nevertheless, their widespread use in transportation analyses requires some linkage between HCM procedures and data and any new procedures used to quantify congestion and mobility on roadways.

Lane Occupancy Rates and Queues. Lane occupancy rates are used increasingly to quantify freeway congestion since relationships between lane occupancy and congestion levels are particularly useful for real-time transportation information systems. This approach is understood well by transportation professionals but is somewhat confusing to the general public. The method provides a reasonable representation of existing freeway congestion, but it cannot be readily used to assess future conditions. Using lane occupancy rates requires the installation/presence of a freeway detector network. These detectors tend to be less accurate under congested conditions. They are becoming more widespread as freeway traffic management systems are installed.

The concept of queues (i.e., backups of traffic) best reflects the public's perception of congestion. Observing queues (and estimating delays from them), however, is a laborious, site-specific, and time-specific task. It is simply not practical to measure queues, except in individual situations. These measures are, therefore, inappropriate for broad planning and/or policy-related analyses.

Queuing measures are typically applied to arterials. The various formulas associated with these measures use v/c ratios for signalized intersections. The steady state assumptions upon which many of these formulas are based can lead to unrealistically high queues when v/c ratios exceed 0.8.

Travel Time Measures. Travel time is well understood by both the professional community and the general public as a measure of congestion. Travel time measures can be used to assess existing conditions and can be applied to various modes of transportation. They can also be used to evaluate transportation and land use interactions with accessibility measures. Travel time measures work well in conjunction with sampling and statistical analyses and can be aggregated. Gridlock and/or queue-propagation effects can also be reflected using travel time measures.

Travel speed has also been used as a measure of congestion. It is perhaps even more easily understood than travel time but is more difficult to aggregate or analyze statistically (e.g., average speed in a network of different volumes and

TABLE 10 Comparison of various congestion measures

Criteria Measure	Early/ Empirical Concepts	Direct Measures					Surrogate Measures		
		Lane Occupancy Rates and Queues[a]	Travel Time Measures				Highway Capacity Manual and HCM-Related Concepts	Headway-Related	Traffic Flow Per Lane, Traffic Pressures, and Congestion Indices
			Time[b]	Speed[b]	Delay	Stops			
1. Clarity and Simplicity									
• Simplicity	No	Yes	Yes	Yes	Yes	Yes	Yes	Possibly	Yes
• Unambiguous	Possibly	Generally	Yes	Yes	Yes	Yes	Yes	Possibly	Yes
• Credible	No	Generally	Yes	Yes	Yes	Yes	Yes	No	Possibly
2. Descriptive/Predictive Ability									
• Describe existing conditions	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Possibly	Yes
• Predict change	No	No	No[c]	No[c]	No[c]	No[c]	Yes	No	Yes
• Test options	No	No	No[c]	No[c]	No[c]	No[c]	Yes	No	Yes
• Reflects traffic flow changes	Possibly	No	Possibly[c]	No[c]	No[c]	No[c]	Yes	Yes	Yes
3. Analysis Capability									
• Economical data requirements	No	No	No[c]	No[c]	No	No	No	No	Yes
• Statistical analysis compatibility	Very Ltd.	No	Yes	Limited	No	No	No	No	Yes
• Consistent Results	Limited	Generally	Yes	Yes	Yes	No	Yes	Possibly	Yes
• Reasonable representation of congestion	Possibly	Yes	Yes	Yes	Yes	No	Generally	No	Possibly
4. General Applicability									
• Various modes	No	No	Yes	Yes	Yes	Yes	No	No	No
• Various facilities	Generally	Generally	Yes	Yes	Art.	Art.	Yes	Rural Art.	Yes
• Time duration of congestion	Yes	Yes	Yes	Yes	Yes	No	Possibly	Yes	Possibly
• Geographic extent (spillback & propagation)	Yes	Yes	Yes	Yes	Ltd.	Ltd.	No	No	Possibly
• Various application scales/settings	Yes	No	Yes	Yes	Ltd.	Yes	Generally	No	Yes
• Various degrees of congestion	Yes	Limited	Yes	Yes	Yes	No	Generally	Possibly	Yes
• Correlates with air quality/energy impacts	Possibly	Yes	Yes	Yes	Yes	No	Yes	No	Possibly

[a] Lane occupancy rates are applied to freeways, while queue measurements are applied to arterials.
[b] Assessments are shown for more promising measures.
[c] Yes, if surrogate measures are used to estimate data.

link lengths). Travel rate (e.g., minutes per mile) is a speed-related quantity that provides the desired statistical and analytical properties.

Traffic Flow per Lane Measures and Congestion Indices. The primary problem with direct measures (such as travel times and lane occupancy rates) is that they are difficult to use in predicting future congestion levels. These measures are not usually available in transportation planning models. The costs and time involved in obtaining data associated with these measures also pose problems. Surrogate measures, such as the "Roadway Congestion Index," have, therefore, been developed. These measures use more readily available data, and their computational simplicity makes them well suited for assessing the impact of traffic growth or transportation facility improvements or for policy analysis. Such measures are, however, not appropriate for detailed operational analyses.

The validity of these measures depends upon the strength of the relationship between traffic per lane, or "traffic pressures," and travel times or speeds—especially when data are stratified by road type, signal density, and other similar factors. The study of these relationships is documented in the next chapter of this report.

Miscellaneous Measures. Additional congestion measures include the quantification of headway distribution and passing opportunities. The use of these measures is limited to rural highways. Such measures are not easily understood and have not been widely accepted or used. The ability of these measures to quantify congestion is not clear.

Summary of Congestion Measurement Evaluation

The analysis summarized in Table 10, supported by the preference of surveyed agencies for time and delay measures, led the study team to **recommend that travel time–based measures be used to estimate congestion levels.** The needs identified in the discussion of users, uses, and the audiences for congestion, when placed in the context of the evaluation criteria, can best be satisfied by measures such as travel time, travel speed, travel rate, and travel delay. In most situations, the use and presentation of congestion information should be in travel time–related quantities.

This section of the report addresses some of the reasons for the recommendation. The problems that might be encountered by agencies and groups adopting the policy are also discussed. Remedies for those problems, or possible alternatives that require more study, are identified and discussed in this and subsequent chapters. The data collection procedures are described in detail in the User's Guide prepared as part of this project.

Conclusions from each of the evaluation criteria are based on the following detailed information developed for Table 10. More detail on each of the measurement techniques is included in the Interim Report for NCHRP Project 7-13 (*7*).

Clarity and Simplicity. Several types of measures score well on this important criterion. In light of the ISTEA requirements for increased citizen participation and the involvement of a range of private sector business interests in evaluating, funding, and constructing or implementing transportation improvements, this criterion will be important for many congestion measurement uses. The direct travel time measures and the HCM and traffic pressure and index surrogate measures can provide information in very understandable forms. Lane occupancy and queuing analyses are also generally able to provide clear and simple measures.

Descriptive and Predictive Ability. Surrogate measurement techniques perform best in this criterion. Their use of traffic counts (along with other predictable parameters such as road geometry and signal spacing) as the basis for analysis means that the prediction of future or changed conditions is relatively easy compared to direct measures. **This points to the need for a set of surrogate measures as part of the final product of this study.** The direct travel time measurement techniques cannot produce estimates of changed conditions easily; this does not rule out the use of travel time measures, but rather means that the output from surrogate measures should be expressed in travel time quantities and related to actual measurements.

Analysis Capability. Direct measures of travel time have required substantial effort to collect under standard practice. Conditions are changing, however, and it is from the perspective of advanced technologies now being implemented in many areas that the analysis capability criteria have been applied. Taking advanced technologies into account, the data collection and analysis requirements included in this set of criteria are best satisfied by direct measures of travel time. The intelligent transportation systems technologies are very amenable to the automated collection and analysis of travel time and speed data.

Even without these systems, careful application of sampling in travel time and speed data collection can provide the amount of information required at acceptable cost. Collection of travel time data does not have to be accomplished on all roads or facilities being analyzed.

The collection of traffic volumes and estimation of capacity required in HCM procedures also are costly and time consuming, although most agencies are reasonably accomplished in performing these analyses. Statistical analyses are easier to perform on freeways than arterial streets, using automated data collection processes associated with advanced freeway operations systems. The statistics produced from HCM analyses are very useful for operational evaluations, but must be transformed into delay and speed-related measures to produce congestion statistics.

General Applicability. The direct data collection methodologies are the most useful for the range of modal, temporal, and spatial extent of congestion analyses. Directly collected data provide information that can be compared for a variety of different routes or modes in a single procedure using one quantity. They can be used for individual routes or combined for several routes or an entire area using sampling techniques. Current HCM analyses cannot handle congestion impacts of public transport and have difficulty with time and spatial extent measures. They are useful for environmental analyses in that the results are generally consistent with air quality or energy consumption conclusions although, as with the direct measures, they are not detailed enough to provide all the information needed for some types of environmental assessments.

Conclusions

The presentations of congestion information identified in the "needs" section of this report and analyzed by the criteria in Table 10 are clearly best satisfied by travel time or rate measures. This fact does not preclude the use of other procedures, including surrogates in certain situations. The key point to consider when developing a set of congestion measures is that the information should be analyzed and presented in the form that best suits the needs of the analysis.

Although the issues of data collection requirements and procedures are included in Table 10, they are, in some respects, a separate issue. **Accordingly, it is useful to separate the data collection requirements from the way the data are used and presented to the audience.**

The following sections address some of the reasons for the separation of data collection and analysis presentation. Problems that might be encountered by agencies and groups adopting this policy are also discussed. Remedies for those problems, or possible alternatives that require more study, are identified and discussed in this and subsequent chapters. The data collection procedures are discussed in more detail in the User's Guide prepared as part of this project.

Some members of the NCHRP Project 7-13 Review Panel and other outside reviewers of this work have expressed concern about using travel time measures. Many of these concerns relate to data collection procedures and costs. The Study Team agrees that the state of the practice in transportation data collection is not to the point where the widespread **direct collection** of travel time and speed data from the traffic (or travel) stream is a realistic possibility. However, when the needs of the variety of customers identified for congestion statistics are considered, there is no better method of **analyzing** improvement alternatives and **presenting** that congestion information than using travel time and speed measures.

Sampling procedures can provide useful travel time and congestion information from relatively limited data collection budgets. Moreover, the future holds great promise for significant improvements in data collection techniques. Advanced technologies are already providing quantum increases in travel time data that are available for transportation analyses even to the point that collected data must be sampled for many uses. As these systems are installed in cities, travel time information will be more available in at least some corridors, and will become more familiar to transportation professionals and the audiences they serve.

RECOMMENDED CONGESTION MEASURES

Developing a system of congestion measures should be initiated only after an examination of the uses, users, and audiences highlighted earlier in this report, a full consideration of program goals and objectives, and the identification of the nature of likely solutions. The measures offered here illustrate a range of techniques that use travel time–based measures to estimate congestion levels. These procedures are useful for roadway systems, other person and freight movement modes, and transportation improvement strategies and programs.

Travel time and delay should be the foundation for the primary system of congestion measurement. This section provides a summary of the basic measures of congestion that can be calculated using travel time, traffic volume, and roadway inventory data. The definition, calculation procedures, required data items, scale of analysis, and applicability to analysis are presented for each measure.

Data Items

This section describes the basic data elements that are used to define the congestion measures.

Travel time is the time required to traverse a segment or complete a trip. Times may be measured directly using field studies, or can be estimated using empirical relationships with traffic volume and roadway characteristics, computer network models, or the intended effects of improvements.

Acceptable travel time is the time that indicates a system or mode is operating according to local performance goals. It focuses on the "door-to-door" trip time from origin to destination. The acceptable travel time is differentiated by the purpose of travel, the expectation for each mode within the transportation system, and the time of day, and should be influenced by community input particularly on the issue of the balance between transportation quality, economic activity, land use patterns, and environmental issues.

Segment or trip length is the distance associated with the travel time. Length can be measured directly with a vehicle odometer or scaled from accurate maps, but is typically an established item in a transit or roadway inventory database.

Average speed for a segment can be used to calculate travel rate or travel times if field data are not readily available.

Actual travel rate is the rate, in minutes per mile or kilometer, at which a segment is traversed or a trip is completed. Travel rates may be determined directly using travel time field studies, or can be estimated using transit schedules or empirical relationships between traffic volume and roadway characteristics.

Acceptable travel rate is the maximum rate of travel (or lowest travel speed) at which a segment is traversed or a trip is completed without experiencing an unacceptable level of mobility. The acceptable travel rate should be based on technical factors that reflect the role and expectation of each portion of the transportation system, and should also be influenced by community input.

Vehicle volume is the number of vehicles traversing the segment that is associated with the travel time. Traffic volumes may be collected using field studies or estimated using standard procedures, but are typically an established item in a roadway inventory database.

Person volume is the number of people traversing the segment being studied. The person volume can be collected for each travel mode, or estimated using average vehicle occupancy rates for types of vehicles.

Basic Measures

Travel time, speed, and rate quantities are somewhat more difficult to collect and may require more effort than the traffic volume counts that currently provide the basis for most congestion estimation procedures. Travel speed–related measures can, however, be estimated as part of many analysis processes currently used. The ultimate implementation of a set of speed-related measures and analysis procedures in most urban areas will probably rely on some surrogate measures. These measures may include current HCM-based analysis techniques, vehicle density measures taken from detectors in the pavement or from aerial surveys, or relationships that estimate travel rate or speed from generally available volume and roadway characteristics such as those suggested in this report. The use of surrogates will be particularly important in setting policy and the prioritization of transportation improvement projects.

This section describes the measurements that form the basis for the congestion analyses performed in the variety of situations described in Chapter 4 of this report.

Travel time or **difference in travel time** can be used as a basic measure. It can be used to compare door-to-door travel times by different modes. A common use of comparison by travelers is for determining mode or route choice, or time of departure. Used in comparison with acceptable travel time or travel times for alternative transportation and land use configurations, it becomes a congestion measure for both the transportation system and the arrangement of land uses, responsive to the trip length reduction afforded by allowing or encouraging mixtures of residential, commercial, and office land uses. Figure 4 illustrates another comparison—peak to off-peak period travel time. Travel time is also useful in assessing the economic costs of congestion.

The travel rate is the rate of motion, in minutes per mile, for a specified roadway segment or vehicle trip and is another basic measure for many analyses. It is the inverse of speed (multiplied by a conversion factor) and is calculated by dividing the segment travel time by the segment length. While this quantity is not readily understood by all the audiences for congestion measures, it is extremely useful for intermediate calculations, and is more directly related to the quantity used by travelers in their trip planning (travel time) than speed of travel.

This measure can be averaged for a facility, geographic area, or mode, unlike travel speed which is difficult to use directly in formulas and spreadsheets. The standard deviation can be calculated to obtain estimates of trip time reliability and can be compared to a target value representing an acceptable level of congestion or inadequacy of mobility. Ratios of values also may be used instead of absolute differences to quantify congestion.

$$\begin{aligned}\underset{(minutes\ per\ mile)}{Travel\ Rate} &= \frac{Travel\ Time\ (minutes)}{Segment\ Length\ (miles)} \\ &= \frac{60}{Average\ Speed\ (mph)}\end{aligned} \quad (9)$$

The delay rate is the rate of time loss for vehicles operating in congested conditions, expressed in minutes per mile, for a specified roadway segment or trip. It is calculated as the difference between the actual travel rate and the acceptable travel rate. The delay rate can also be calculated by dividing the difference (in minutes) between the actual travel time and the acceptable travel time by the segment length (in miles). The quantity can be used to estimate the difference between system performance and the expectations for those system elements, which can be used to prioritize alternative improvements.

$$\begin{aligned}\begin{matrix}Delay\ Rate\\(minutes\\per\ mile)\end{matrix} &= \begin{matrix}Actual\\Travel\ Rate\\(minutes\ per\ mile)\end{matrix} - \begin{matrix}Acceptable\\Travel\ Rate\\(minutes\ per\ mile)\end{matrix} \\ &= \frac{\begin{matrix}Actual\ Travel\ Time\\- Acceptable\ Travel\ Time\end{matrix}}{Trip\ or\ Segment\ Length\ (miles)}\end{aligned} \quad (10)$$

Total delay for a transit or roadway segment is the sum of time lost due to congestion, typically expressed in person- or vehicle-hours. Total delay in a corridor or an urban area is calculated as the sum of individual segment vehicle or person delays. This quantity is used as an estimate of the impact of improvements on transportation systems. The values can be used to illustrate the effect of major improvements to one portion of a corridor that affect several other elements of the corridor transportation system, either by improving travel rate or by drawing person travel away from portions of the system that do not perform well. The quantity is particularly useful in economic or benefit/cost analyses that require information on cost effectiveness.

$$\underset{(person\text{-}hours)}{Total\ Delay} = \left[\underset{(minutes)}{\overset{Actual}{Travel\ Time}} - \underset{(minutes)}{\overset{Acceptable}{Travel\ Time}} \right] \times \underset{(persons)}{\overset{Person}{Volume}} \times \frac{hours}{60\ minutes}$$

$$= Delay\ Rate \times Person\ Volume \times Segment\ Length \tag{11}$$

The relative delay rate is a dimensionless measure that can be used as a congestion index to compare the relative congestion on facilities, modes, or systems in relation to different mobility standards for system elements such as freeways, arterial streets, and transit routes. It is calculated as the delay rate divided by the acceptable travel rate. The acceptable travel rate can reflect differences in operation between transit and roadway modes, allowing the relative delay rate to be used to compare different parts of the transportation system. The relative delay rate can illustrate that a delay rate of 1 min per mile on a freeway (e.g., 2 min per mile versus an acceptable rate of 1 min per mile) is much more significant than a similar delay rate on a downtown street (e.g., 5 min per mile versus an acceptable rate of 4 min per mile).

$$\underset{Delay\ Rate}{Relative} = \frac{Delay\ Rate}{Acceptable\ Travel\ Rate} \tag{12}$$

The delay ratio is a dimensionless measure that can be used to compare or combine the relative congestion levels on facilities with different operating characteristics like freeways, arterial streets, and transit routes. It is calculated as the delay rate divided by the actual travel rate. The delay ratio identifies the magnitude of the mobility problem in relation to actual conditions (as opposed to the relative delay rate that compares system operations to a standard).

$$Delay\ Ratio = \frac{Delay\ Rate}{Actual\ Travel\ Rate} \tag{13}$$

Speed of person movement is a measure of travel efficiency that could be used to compare the person movement effectiveness of various modes of transportation. The measure is calculated as the product of passenger volume and average speed for a particular route, and is typically expressed in terms of person-miles per hour. This quantity combines two desirable attributes for elements of the transportation system: speed of travel, and the number of persons being moved. The value increases as either quantity increases. This measure can provide comparisons between alternative transportation improvements if a weighted average value of all corridor treatments is used. One problem with this value is that the size of the number is relatively large and difficult to compare to a standard or baseline value.

$$\underset{(person\text{-}mph)}{Person\text{-}Speed} = \underset{(persons)}{Person\ Volume} \times \underset{(mph)}{\overset{Average}{Travel\ Speed}} \tag{14}$$

The corridor mobility index consists of the speed of person movement value divided by some standard value, such as one freeway lane operating at nearly peak efficiency with a typical urban vehicle occupancy rate. This may be one method of addressing the magnitude and relativity problems with the speed of person movement. For instance, a freeway lane operating at high speed and volume might have a volume of 2,100 vehicles per hour at 50 mph. With an occupancy rate of 1.2 persons per vehicle the normalizing value would be approximately 125,000. A similar value can be calculated for an arterial street lane using a capacity of between 1,600 and 1,800 vehicles per hour, 50 to 60 percent green time on the road being analyzed, and operating speeds between 20 mph and 25 mph. A normalizing value of approximately 20,000 to 25,000 appears reasonable for arterial streets. The corridor mobility index, therefore, provides a relative value that can be used to compare alternative transportation improvements (e.g., high-occupancy vehicle treatments) to traditional improvements such as additional freeway lanes.

$$\underset{Index}{Corridor\ Mobility} = \frac{Speed\ of\ Person\ Movement}{\underset{(e.g.,\ 25{,}000\ or\ 125{,}000)}{Normalizing\ Value}} \tag{15}$$

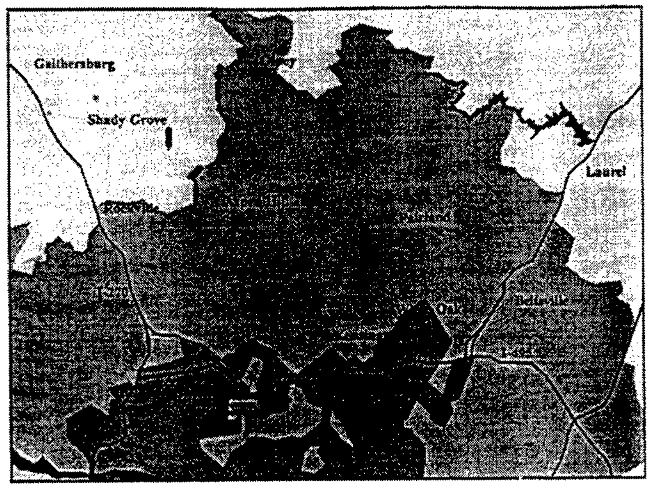
Accessibility at an individual location can be simply measured as the number of opportunities for travel objective fulfillment that can be reached within an acceptable travel time. One single acceptable travel time is used for each type of objective (travel purpose), mode of transportation, and time of day, irrespective of distance. Opportunities for fulfillment of travel objectives can be represented by employment (jobs), housing, shopping, community services, or other destinations of interest. Percentages can be calculated by dividing accessible objectives by the corresponding total (e.g., percentage of total jobs). Weighted averages or the median value can be derived for a corridor or region. More complex formulations based on trip distribution model formulations are possible.

Accessibility is most readily calculated using transportation planning computer networks and demographic data for a corridor or region (Equation 16). It has been extensively used for assessing relative quality and equity in transit service, but can be applied to any mode. The strongest feature of accessibility is that it is particularly useful in examining the joint performance of the transportation and land use system.

$$\underset{(opportunities)}{Accessibility} = \sum \begin{array}{c} Objective\ Fulfillment \\ Opportunities\ (e.g.,\ jobs),\ Where \\ Travel\ Time \le Acceptable\ Travel\ Time \end{array} \tag{16}$$

Figure 5 illustrates two accessibility measure maps. One map illustrates accessibility of all activities. The top map can be used to present either existing conditions, future trends, or the results of improvements to either transportation or land use systems. Improvements or alternative arrangements can also be examined by identifying the differences compared with existing conditions or the base case as illustrated in the bottom map. This type of map clearly identifies the area affected and the magnitude of the effect of transportation or land use actions.

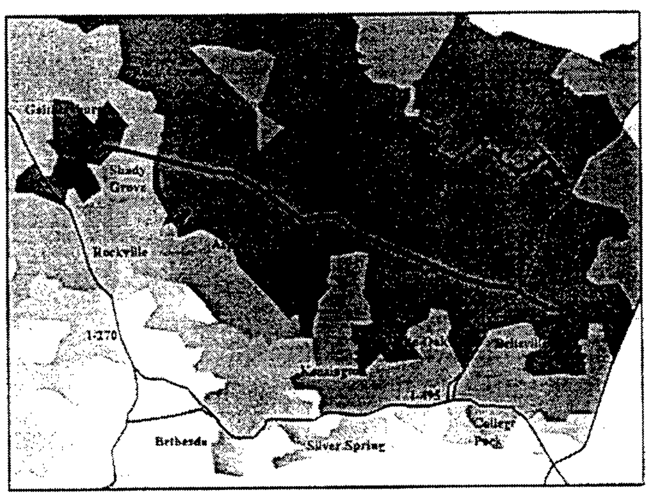
Congested travel is the amount of travel (in vehicle-miles or person-miles) that occurs in congestion. It is calculated by multiplying the length of a congested segment by the vehicle traffic or person volume associated with the appropriate time period, then summing the congested travel over all segments.



LEGEND
Freeways
Rivers & Lakes

Jobs Reached by Roads within 45 min.
0-250,000
250,001-400,000
400,001-600,000
600,000+

Job Accessibility Before Construction of Inter-County Connector



LEGEND
Master Plan Alt.
Freeways
Rivers & Lakes

Additional Jobs Reached by Roads
Minimum Impact
25,000-50,000
50,001-100,000
100,000+

Job Accessibility After Construction of Inter-County Connector

Prepared by the Metropolitan Washington Council of Governments for the Maryland Department of Transportation, State Highway Administration, Intercounty Connector (ICC) Project Planning Study

Figure 5. Accessibility measurement for a proposed improvement in an urban area.

$$\begin{array}{c}\textit{Congested}\\ \textit{Travel}\\ (\textit{person-miles})\end{array} = \sum \begin{bmatrix} \textit{Congested} & & \textit{Person} \\ \textit{Segment Length} & \times & \textit{Volume} \\ (\textit{miles}) & & (\textit{persons}) \end{bmatrix} \qquad (17)$$

Congested roadway describes the extent of congestion (in miles) on the roadway or transit system. It is calculated by summing the congested segment lengths.

$$\begin{array}{c}\textit{Congested Roadway}\\ (\textit{miles})\end{array} = \sum \begin{bmatrix} \textit{Congested Segment} \\ \textit{Length } (\textit{miles}) \end{bmatrix} \qquad (18)$$

Congestion Measures for Types and Levels of Analysis

Table 11 summarizes the congestion measures to be used for several analysis (or scale) levels. Travel rate and delay rate are very useful for analysis up to the corridor level. At higher levels of analysis, cumulative statistics such as delay and congested travel and roadway are more useful. Indices are also useful methods of quantifying congestion in large areas. Examples of the application of these congestion measures to situations based on the level of analysis are included in Chapter 4.

An advantage of travel time and speed measures becomes apparent during identification of appropriate congestion measures. The recommended measures in Table 12 vary by the scope of the analysis but not by mode or facility type. Different values will be used for acceptable travel rate or acceptable travel time depending on the facility type of travel mode, but the calculation and application of the measures is identical.

The analysis and presentation of congestion data for individual locations and short sections of roadway can be accomplished by travel time, travel rate, delay rate, total delay and delay per vehicle or person as primary measures. These studies are at a relatively small area and individual vehicle or person level statistics are very useful and illustrative. Total delay and delay per person or vehicle are most useful for intersections or individual locations due to problems identifying the length needed for the rate-based measures. Secondary measures may also be used for cumulative analyses of several improvements and estimation of benefits.

Congestion for larger areas of analysis such as long roadway sections and corridors can be quantified with some individual statistics if the roadways are of the same type, but if both freeways and streets are included, cumulative statistics and the relative delay rate and delay ratio are very appropriate. Index statistics also become useful at this higher level of analysis when multiple roadways and large numerical values make interpretation of relative conditions difficult.

Analyses that combine more than one travel mode are particularly easy using travel time and person volume measures. The relative delay and delay ratio can be used to accommodate the differences in travel conditions for each mode individually. Indices can also be used to evaluate these situations.

While it is difficult to cover every type of congestion analysis, Table 12 illustrates recommended congestion measures for many common types of studies and information requirements. As with the level of analysis table (Table 11), the uses with an immediate need for information or a small

TABLE 11 Recommended congestion measures for analysis levels

Level or Scale of Analysis	Measures of Congestion										
	Travel Time	Travel Time Difference	Travel Rate	Delay Rate	Total Delay	Relative Delay Rate	Delay Ratio	Corridor Mobility Index	Congested VMT/ PMT	Congested Roadway	Accessibility
Individual Locations	S	S			P						
Short Roadway Sections	P		P	P	S	S					
Long Roadway Sections or Routes		S	P	P	P	S	S				
Corridors			S	S	P	P	P	S			S
Sub-Areas					P			S	P	P	P
Regional Networks					P			S	P	P	P
Modal Analyses		P	S	S	P	P	P	P			P

Note: P = Primary measure of congestion
S = Secondary measure of congestion
VMT = Vehicle-miles of travel
PMT = Person-miles of travel

TABLE 12 Recommended congestion measures for various types of analyses

Uses of Congestion Measures	Measures of Congestion										
	Travel Time	Travel Time Difference	Travel Rate	Delay Rate	Total Delay	Relative Delay Rate	Delay Ratio	Corridor Mobility Index	Congested VMT/ PMT	Congested Roadway	Accessibility
Identification of problems	P	P	P	P	S						
Basis for government investment or policies					P			S	P	P	P
Prioritization of improvements				P	P	P	P		S	S	S
Information for private sector decisions	P		P	P	S						
Basis for national, state, regional policies and programs					P				P	P	P
Assessment of traffic controls, geometrics, regulations	P		P	P		S	S				
Assessment of transit routing, scheduling, stop placement	P	P	P	P	S						
Base case (for comparison with improvement alternatives)		P		S	P			P			P
Inputs for transportation models	P		P	P							
Inputs for air quality and energy models	P		P	P							
Measures of effectiveness for alternatives evaluation			P	P	P			P			P
Measures of land development impact	P	S	P	P	P						P
Input to zoning decisions	P	P	P								P
Basis for real-time route choice decisions	P	S	P	P							

Note: P = Primary measure of congestion
S = Secondary measure of congestion
VMT = Vehicle-miles of travel
PMT = Person-miles of travel

area being analyzed require smaller and simpler units of measure. The more complex analyses, or those that typically cover larger areas, will be more amenable to some of the index measures, or summary statistics.

Collection of Congestion Data

Travel time data have not been widely collected for existing conditions in the recent past because of the expense of data collection relative to traffic volume counting programs. This issue is addressed in Chapter 3 of this report and in the accompanying User's Guide. If the two-track approach recommended by this research report is used—both directly collecting congestion data *and* using surrogate travel speed estimates derived from a number of sources—transportation analysis agencies and groups will be able to devise cost-effective data collection programs and use measures that are consistent with the range of analytical and presentation needs.

Travel time, as a general rule, should be measured (or sampled) directly for existing conditions. These measurements should reflect both peak and off-peak operating conditions by direction of travel. Quantifying the congestion over a roadway system should involve weighing the time differences (or ratios) mentioned previously by the vehicle and/or passenger volumes associated with the defined system.

The guidelines also refer to collecting travel time and speed data on a sample set of roadways in the analysis area. The use of stratified sampling techniques allows congestion measurement programs to be more affordable, especially for large study areas.

The ultimate use of the information should be considered when designing a data collection program. It may be appropriate to measure congestion directly at a few locations where congestion is very severe and to sample the remaining roadway system. There may be sections, for example, where geometric bottlenecks cause much lower speeds over longer distances than are typical for roadways with similar volumes. If the goal of the analysis is to identify the areawide magnitude of congestion, the severity of the problem, and the location of the most significant congested areas, the process should start with the local transportation experts identifying the known congested areas and, in at least a general way, categorizing their severity.

The collection of vehicle occupancy data is also important for some analyses, but it may not be necessary for many others. Where modal alternatives may be studied, or the effect of ridesharing, pricing, parking, or other policies designed to encourage a mode shift away from the single-occupant vehicle, occupancy data are very useful. The frequency and facilities and areas covered by such data collection also should be examined to extract the most appropriate level of information with the lowest expenditure. A few studies in an area every 2 or 3 years may be all that are required to obtain information on the "background" or normal vehicle occupancy rate for different travel periods.

Analyzing future conditions, alternative improvements, or prioritizing projects would require the use of surrogate (indirect measures of congestion) measurement techniques to estimate the travel rate for various situations. A systematic process with several factors would be used to estimate travel rate values, which would then be used in the same manner that the direct measures are used.

Travel time in existing conditions should be estimated using the same surrogate techniques when it is to be presented in comparison with travel time estimated for future or other new conditions. This exception to the general rule of direct data collection is necessary to avoid findings that are no more than artifacts arising from the use of different measurement techniques.

CHAPTER 3

FINDINGS—TRAVEL TIME AND SPEED ESTIMATES

OVERVIEW

This chapter describes the data collection efforts that were performed to validate the recommended congestion measures. The sections set forth sampling procedures for travel time data over time and space and for estimating vehicle occupancy. "Surrogate" estimating procedures are included for estimating travel times and speeds when field data are not available. Equations, tables, and charts provide user-friendly guidelines for quantifying congestion.

DATA COLLECTION AND ANALYSIS

This section describes the travel time and speed data collected for this project, the analysis of variation in the data, and the development of predictive relationships for travel speed. The Study Team involved several agencies in the data collection process to maximize the amount of data available and to test the data collection procedures developed for the User's Guide. The agency-supplied data were supplemented by data collected from Texas cities for other projects.

The information on speed characteristics and variability will assist agencies preparing travel speed studies to identify sample sizes required. The relationships are described using a stratification process to improve the predictive ability. The ranges in the data also are displayed to identify the variability in the relationships. This section also contains guidelines for estimating vehicle occupancy.

Participating Agencies and Obtained Data

A summary of the participating agencies is contained in Table 13. A total of 19 agencies submitted travel time data for use in this research project. Two of the 19 agencies' data could not be used because of inconsistent data collection procedures. Several agencies collected data specifically for this NCHRP project; however, most agencies had data collection efforts programmed for their agency and considered NCHRP guidelines in collecting the data. Several other agencies had existing travel time data that were consistent with the NCHRP guidelines. In addition to the travel time data, agencies were asked to submit geometric and traffic information like the number of lanes, average daily traffic (ADT) volumes, peak-hour traffic volumes, speed limits, signal frequency and coordination, percent green, and several other items. The traffic information was used to develop stratification factors and surrogate travel time estimation procedures. Several agencies did not submit the traffic information required for the development of the surrogate travel time estimation procedure.

The first 14 agencies in Table 13 collected travel time data at a large number of different sites (i.e., roadway segments). These data were primarily used to examine the spatial or "between-route" variation that exists between segments of different roadways, and also to develop a travel time estimation procedure. These data consist of many segments with a minimum number of runs for each segment. The last three data sources consist of travel time data that have been collected over time on a limited number of freeway segments and provide information about the "within-route" variation that occurs from day to day on a particular roadway segment.

The following sections discuss the results of the statistical analysis in the sampling procedures that are necessary to collect travel time data and the surrogate procedures that are necessary to estimate travel times.

Summary of Sampling Analysis Procedures and Parameters

The following sections describe the various analyses that were related to the direct sampling of travel times. The sampling issues investigated in the analysis include the following:

- Number of travel time runs for a roadway segment.
- Number of segments to sample within a region or urban area.

Because travel time sampling is directly related to travel time variability, the sampling procedures analysis examined the variability of the travel time data collected by the various agencies in Table 13. The "within-route" variability, or variability over time for a given segment, was analyzed to determine the required number of travel time runs for that given segment. The "between-route" variability was analyzed to determine the required number of segments to sample within a region or urban area.

General Analysis Techniques. The travel time, traffic, and other identifying data were entered into a fixed-column, ASCII-text file format. Each line of the data represented a travel time observation. Separate data files were maintained

TABLE 13 Summary of participating agencies and submitted data

Data Source	Data Collection Technique	Submitted Data	
		Freeways	Arterial Streets
Bristol Metropolitan Planning Organization (Tennessee)	Floating Car	none	482 observations on 18 segments
Chicago Area Transportation Study	License Plate Matching	none	282 observations on 94 segments
Connecticut Department of Transportation	Floating Car	none	146 observations on 20 segments
Champaign-Urbana Urbanized Area Transportation Study (Illinois)	Floating Car	none	1,434 observations on 264 segments
DuPage County Division of Transportation (Illinois)	Floating Car	none	3,477 observations on 1,159 segments
Indianapolis Department of Metropolitan Development	Floating Car	44 observations on 22 segments	610 observations on 305 segments
Maryland State Highway Administration	Floating Car	none	86 observations on 8 segments
Memphis, Shelby County Office of Planning and Development/Memphis MPO	Floating Car	none	117 observations on 24 segments
Metropolitan Washington Council of Governments (MWCOG)	License Plate Matching	none	1,913 observations on 22 segments
North Carolina Department of Transportation	Floating Car	10 observations on 2 segments	94 observations on 18 segments
Nevada Department of Transportation	License Plate Matching	3,421 observations on 16 segments	none
Ohio Department of Transportation	Floating Car	541 observations on 163 segments	768 observations on 253 segments
Southeastern Regional Planning and Economic Development District (Massachusetts)	License Plate Matching	none	1,285 observations on 30 segments
City of Springfield Department of Planning and Development (Missouri)	Floating Car	none	139 observations on 20 segments
Texas Department of Transportation—Planning Division	Floating Car	19,560 observations on 30 segments	none
Houston Cellular Phone Demonstration—Texas Transportation Institute	Cellular Phone "Probe Vehicle"	169,874 observations on 40 segments	none
Houston Traffic Monitoring System Phase One—Texas Transportation Institute	AVI Tags "Probe Vehicle"	Approx. 29,000 daily observations on 60 segments	none

for each data source, which allowed separate analyses for each data source if desired. The PC-SAS computer program was used to read the travel time observations and perform all statistical analyses.

After examining some of the data sets for reasonableness and consistency, the researchers discovered that basic statistics like the mean, standard deviation, and coefficient of variation were different for the travel rate and travel speed distributions (Table 14). Although travel rate and travel speed are essentially the inverse of each other, a non-normal data set can produce different statistical results for travel rate and travel speed distributions. The problem of non-normal distributions was most often encountered with low values of speed or low values of travel rate (Figure 6). With a normal distri-

TABLE 14 Illustration of difference in travel rate and speed distributions, example data

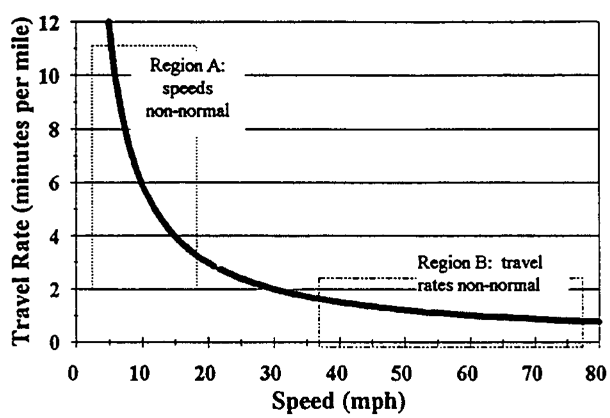
Example of Normal Data Set		Example of Non-Normal Data Set	
Travel Rate (minutes per mile)	Speed (mph)	Travel Rate (minutes per mile)	Speed (mph)
1.20	50	4.00	15
1.20	50	4.00	15
1.09	55	4.00	15
1.09	55	1.50	40
1.09	55	1.33	45
1.00	60	1.33	45
1.00	60	1.00	60
1.00	60	1.00	60
0.92	65	1.00	60
0.92	65	1.00	60
Mean=1.05 m/m Std. Dev.= 0.10 m/m c.v.=9.5%	Mean=57.5 mph Std. Dev.= 5.4 mph c.v.=9.4%	Mean=2.02 m/m Std. Dev.= 1.38 m/m c.v.=68.5%	Mean=41.5 mph Std. Dev.= 19.7 mph c.v.=47.5%

Notes: Std. Dev.—Standard deviation
c.v.—coefficient of variation
m/m—minutes per mile

bution, however, there is little to no difference between the coefficients of variation for travel rates and speeds.

A more comprehensive analysis technique was used to overcome this problem in calculating coefficients of variation, and was originally suggested by Berry in his early travel time studies (*59,60*). The distribution of travel rates (which is identical to the distribution of travel times) and travel speeds were examined for normality using the skewness value, which is a measure of the tendency of variation to be larger in one direction (positive or negative) than the other. The travel rate or speed distribution that was more normal, as indicated by the lower skewness value, was used to calculate coefficients of variation. The use of this technique produced reasonable results that are more consistent with estimates of travel time variability contained in the literature.

Stratification of Travel Time Data. The required sample sizes for travel time data collection are directly related to the variability of travel time data. Several statistical techniques can be used to minimize the variability and, conse-



Speed (mph)	Travel Rate (min/mile)
5	12.00
10	6.00
15	4.00
20	3.00
25	2.40
30	2.00
35	1.71
40	1.50
45	1.33
50	1.20
55	1.09
60	1.00

Region A: Low speeds, high travel rates
Speeds sometimes non-normal
Typically use c.v. from rate distribution

Region B: High speeds, low travel rates
Travel rates sometimes non-normal
Typically use c.v. from speed distribution

Figure 6. Relationship between speed and travel rate.

quently, the sample sizes necessary for a given level of confidence and specified error. Stratified random sampling minimizes variation by using groups of roadway segments with similar operating characteristics. Each stratum group in the sampling plan encompasses roadways with similar traffic and control characteristics, with the expectation that travel speeds will be similar (i.e., low variability) within that group. Grouping similar roadway segments into a stratum group results in reduced variability for each group. The sum of the random samples required for the individual stratum groups is smaller than for the group as a whole.

The analysis attempted to identify the stratification variables that would have the greatest effect in reducing travel time variability while simultaneously producing manageable sampling plans. It was clear that freeways and arterial streets should form separate strata and that further stratification within each group was also desirable.

The stratifications were based upon analysis of variations in travel times by both individual speed runs and individual segments. The means, standard deviations, and coefficients of variation were based upon almost 6,600 individual arterial observations and 4,100 freeway observations. Thus, they reflect the composite of variations *within and among* segments. Therefore, the variations were larger than those when considering speed or travel time runs within a given segment. However, they served to identify those variables that proved most meaningful.

The analysis for arterial streets examined five potential stratification variables: arterial class, signal density, ADT per lane, traffic pressure (ADT or directional peak hour lane volume divided by percent green), and signal coordination. The analysis indicated no clear advantage to stratifying the data by traffic pressure or signal coordination, and these two variables were dropped from further consideration in the stratification analysis.

Arterial classes are defined in the 1994 *Highway Capacity Manual* based on the arterial street's function and design. Factors like free-flow speed, access control, signal density, and roadside development all contribute to the definition of arterial class. The 1994 HCM also defines distinct level of service (LOS) criteria for the three different arterial classes. Because arterial street function and design characteristics were considered to be an important stratification variable, arterial class was used in subsequent analyses.

The data were then stratified by the following signal density ranges for all arterial classes:

- Low signal density: Less than three signals per mile.
- Medium signal density: Three to six signals per mile.
- High signal density: Greater than six signals per mile.

The data were also stratified for all arterial classes by the following daily volume per lane values:

- Light ADT per lane: Less than 5,000 vehicles per lane per day.
- Moderate ADT per lane: 5,000 to 9,000 vehicles per lane per day.
- Severe ADT per lane: Greater than 9,000 vehicles per lane per day.

The analyses for freeways examined two potential stratification variables: ADT per lane and access point frequency. This led to the following two stratification groups:

- Light ADT per lane: Less than 15,000 vehicles per lane per day.
- Moderate ADT per lane: 15,000 to 20,000 vehicles per lane per day.
- Severe ADT per lane: Greater than 20,000 vehicles per lane per day.

- Low Access Frequency: Less than one access point per mile.
- Medium Access Frequency: One to two access points per mile.
- High Access Frequency: Greater than two access points per mile.

These stratum groups were used in future analyses of both within-route and between-route variation. Travel time coefficients of variation were examined for freeway and arterial street segments in approximately 15 different urban areas. This analysis produces coefficients of variation for use in subsequent sample size estimates.

1. Arterial Streets. The travel time data were summarized for each arterial street section and a coefficient of variation (c.v.) was calculated. This coefficient of variation characterizes the relative variability for each section based on the number of travel time runs. Average and 85th-percentile coefficients of variation were then calculated for the arterial streets. The sections were then grouped according to the various stratum groups suggested earlier, and it was determined whether this stratification process reduced the average within-route variability for each group.

Considering **no stratification** of the arterial street data set, the following summary statistics were obtained:

Number of Observations:	862 sections
Average coefficient of variation (c.v.):	11.0%
85th-percentile coefficient of variation (c.v.):	17.4%

The roadway sections were then grouped into various strata to reduce the average within-route variability for each group.

- Table 15 contains the summary statistics when the data are stratified by the arterial class. This table illustrates that grouping the arterial street sections by arterial class does not significantly reduce the within-route c.v., which is used to predict the number of runs necessary for a given section.

TABLE 15 Summary of arterial street variability by arterial class

Arterial Class	Number of Street Sections	Average c.v. (%)	85th-percentile c.v. (%)
Class I	560	18.9	29.9
Class II	165	14.7	23.7
Class III	137	11.4	20.6

- Table 16 contains the summary statistics when the data are stratified by the signal density stratum groups suggested earlier. The travel time variation increases as the signal density increases and exhibits a linear relationship. The average c.v.'s range from 9 percent to 15 percent, whereas the 85th-percentile c.v.'s range from 13 percent to 22 percent.
- Table 17 shows the travel time variation for arterial streets stratified by ADT per lane. The variation generally increases as ADT per lane increases, but the linear relationship is not as clear. The average c.v.'s range from 10 percent to 14 percent, whereas the 85th-percentile c.v.'s range from 17 percent to 19 percent.

The use of two stratification factors for within-route variation was also examined. The following combinations were analyzed:

- arterial class and signal density
- arterial class and ADT per lane
- ADT per lane and signal density

The use of two stratification factors did not decrease the c.v. values below those shown in Tables 15, 16, or 17. Therefore, it was decided that one stratification factor would be appropriate for calculation of sample sizes for individual travel time runs.

2. Freeways. The freeway travel time data were summarized for each section, and coefficients of variation were calculated. An average and 85th-percentile coefficient of variation were then calculated for all freeway sections. The sections were then grouped according to the various stratum groups suggested earlier to see how this stratification process reduced the average variability for each group.

Considering **no stratification** of the freeway data set, the following summary statistics were obtained:

Number of observations:	177 sections
Average coefficient of variation:	11.0%
85th percentile c.v.:	18.7%

Freeway travel times were then stratified by ADT per lane and access frequency. Table 18 shows the freeway sections stratified by ADT per lane. The c.v.'s increase as ADT per

TABLE 16 Summary of arterial street variability by signal density groups

Signal Density Stratum Group	Number of Street Sections	Average c.v. (%)	85th-percentile c.v. (%)
Low-Less than 3	320	8.9	13.2
Medium-3 to 6	433	11.7	17.1
High-Greater than 6	109	15.1	21.6

TABLE 17 Summary of arterial street variability by ADT per lane groups

ADT per Lane Stratum Group	Number of Street Sections	Average c.v. (%)	85th-percentile c.v. (%)
Low - Less than 5,000	608	10.3	16.5
Moderate - 5,000 to 9,000	216	12.7	19.3
Severe - Greater than 9,000	38	13.8	18.9

TABLE 18 Summary of freeway variability by ADT per lane groups

ADT per Lane Stratum Group	Number of Sections	Average c.v. (%)	85th-percentile c.v. (%)
Low—less than 15,000	105	9.0	18.1
Moderate—15,000 to 20,000	30	10.5	19.9
Severe—greater than 20,000	42	16.5	25.3

lane increases, and the average c.v.'s range from 9.0 percent to 16.5 percent. These c.v. values are approximately the same as the c.v. values for arterial streets. Table 19 shows the freeway sections stratified by access frequency. The average c.v.'s range from 7.7 percent to 12.0 percent, values slightly lower than those stratified by ADT per lane. Sections with a greater number of entry and exit points are likely to increase merging and diverging conflicts and lane changes and have greater variations in speeds.

Sample Sizes for Data Collection on a Roadway Segment

Average travel times or speeds for a given section of roadway are determined by obtaining several travel time estimates for the period of interest. The travel time estimates can be obtained by performing test vehicle runs, collecting and matching vehicle license plates, or tracking instrumented vehicles as they pass the beginning and end of the study segment (e.g., "probe vehicle").

Each estimate of the segment travel time will vary according to the traffic volume, signal control characteristics, weather, time of day, and other conditions encountered during the run. The individual travel time estimates also vary from day to day and by time of day. The minimum number of runs for each time period and direction of travel should be obtained over several different days of the week to ensure that representative data are being collected. Traffic volumes and conditions on Tuesdays, Wednesdays, and Thursdays are typically representative of average weekday conditions. Automatic traffic recorder stations can be used to help determine ideal days for data collection.

Sampling Concepts and Parameters. The number of travel time runs, or sample size, required to accurately depict the true average travel time is based upon the variation of travel times, the specified error of the travel time estimate, and the desired confidence level (%) of the travel time estimate (Equation 19).

$$\textit{Sample Size}, n = \frac{t_{n-1}^2 \, c.v.^2}{e^2} \tag{19}$$

where

n = number of travel time runs per segment;
t_{n-1} = t-value for Student's t-distribution with $n - 1$ degrees of freedom based on desired confidence level in the travel time estimate (two-tailed test);
$c.v.$ = coefficient of variation of travel time (%); and
e = specified relative error (%), e.g., for $\pm10\%$ error, 30 ±3 minutes.

This equation is somewhat difficult to use in practice since it requires estimates of the number of degrees of freedom in selecting the appropriate t-value. The degrees of freedom depend upon the number of observations that are needed. An iterative procedure is required to find the sample size. Therefore, the normal distribution is commonly used (Equation 20) to estimate sample size.

$$\textit{Sample Size}, n \cong \frac{z^2 c.v.^2}{e^2} \tag{20}$$

where

n = sample size for normal distribution;
z = standard normal variate based on desired confidence level;
$c.v.$ = coefficient of variation of travel times (%); and
e = specified relative error (%), e.g., for $\pm10\%$ error, 30 ±3 minutes.

TABLE 19 Summary of freeway variability by access frequency groups

Access Frequency Stratum Group	Number of Sections	Average c.v. (%)	85th percentile c.v. (%)
Low—less than 1 access point per mile	38	7.7	14.1
Medium—1 to 2 access points per mile	97	9.9	18.9
High—greater than 2 access points per mile	42	12.0	21.2

The normal distribution equation (Equation 20) produces precise results when the standard deviation (or coefficient of variation) of the population is known. Equation 20 also provides a reliable estimate of sample size when n is greater than 30. It provides a reasonable approximation for sample sizes of 20 to 25 or more.

For sample sizes less than 20, however, Equation 20 may understate the sample size by approximately 2 observations. Given the many assumptions inherent in estimating travel time variations and the minimum sample sizes found necessary to depict real-world conditions ($n \geq 5$ observations), the normal distribution (Equation 20) is generally used and accepted in practice. The sample sizes obtained by Equation 20 could, if desired, be increased by about 2 observations to account for the difference between the normal distribution and the Student's "t" distribution (samples less than 30).

The three factors that influence the sample size are (1) the level of confidence that influences the z- or t-values; (2) the allowable error (absolute or relative); and (3) the population sample standard deviation, or coefficient of variation. The desired confidence levels and permitted error should be based on intended uses of the data and established by the responsible agencies within the urban area or state. The desired confidence levels used in this study ranged between 80 percent and 95 percent. Table 20 contains z-values for common confidence levels.

The specified relative error in Equations 19 and 20 denotes the width of half of the total confidence interval. For example, if the sample mean travel time is to be within 10 percent of the true mean, the relative error is set to ± 10 percent and the sample mean may fall either 10 percent above or 10 percent below the true mean. The total width of the confidence interval that is centered about the sample mean is twice the relative error ($2 \times e$) or 20 percent in this example. The specified relative error is based on the particular application of the travel time estimate. For example, a travel time estimate for an operational evaluation in an urban area would require a lower relative error than an estimate for planning purposes in a rural area.

The coefficient of variation (the sample standard deviation divided by the sample mean) is the most problematic factor in sampling travel times because of its typically high variance (and consequently large sample size). The literature contains approximations of speed variations for different area types and roadway facilities, but travel time variance ideally should be calculated from data collected on facilities that are similar to those being sampled. Coefficients of variation ranging from 10 to 20 percent have been reported for arterial streets and freeways.

Previous Studies. Several previous studies have examined travel time variation and recommended sample sizes for individual test runs. In 1949, Berry and Green (*59*) recommended the following minimum number of average test car runs needed to determine the mean travel time with a 10 percent relative error and a 95 percent degree of confidence:

- Progressive signal timing (volumes below capacity)—8 runs.
- Uncoordinated signals (volumes at or near capacity)—12 runs.
- Uncoordinated signals (volumes below capacity)—8 runs.

In a study three years later, Berry (*60*) reported on an evaluation of the floating car and average car methods conducted on two urban arterial streets and three sections of rural highway. Berry suggested minimum sample sizes (Table 21) that range from 5 to 13 runs for 10 percent relative error.

The National Committee on Urban Transportation suggested that between 6 and 12 individual test vehicle runs be performed to develop a representative estimate for a congested urban route. It was also recommended that not more than three runs be performed over one control section during a single peak hour.

Robertson presents travel time and delay study guidelines in the Institute of Transportation Engineers (ITE) *Manual of Transportation Engineering Studies* (*61*). The sample size requirements recommended by Box and Oppenlander were based on the range of permitted error and the range in the first group of collected travel speeds. The following ranges of permitted error were presented, based on the study purpose:

- Transportation planning and highway needs studies: ± 3 to ± 5 mph
- Traffic operation, trend analysis, and economic evaluations: ± 2 to ± 4 mph
- Before-and-after studies: ± 1 to ± 3 mph

The average range in running speeds was determined by calculating the absolute differences between consecutive test runs, in which stopped delays are excluded. Robertson rec-

TABLE 20 Z-values for common confidence levels

Confidence Level (%)	Z-value
80	1.282
85	1.439
90	1.645
95	1.960

TABLE 21 Reported minimum sample sizes for determining mean overall travel speeds on selected test sections

Test Section	Standard Deviation (mph)	Test Vehicle Runs	
		5% Relative Error	10% Relative Error
Signalized Urban Streets			
Two-lane, uncongested	3.0	30	8
Two-lane, congested	2.7	40	10
Multi-lane, uncongested	1.8	18	5
Multi-lane, congested	2.2	50	13
Rural Highways			
Two-lane, 1130 v.p.h.	5.0	25	6
Two-lane, 1440 v.p.h.	5.2	42	11
Four-lane, uncongested	-[a]	-	-

[a] "-" indicates data not available.
Source: Reference (60).

ommended at least two, preferably four, test runs. The range is then estimated by Equation 21, and the sample size is obtained from Table 22.

$$\textit{Average Range in Running Speeds, } R\ (mph) = \frac{\sum S}{N-1} \quad (21)$$

where

S = sum of absolute speed differences and N = number of completed test runs.

Suggested Sample Size Estimates for Arterial Streets. The analyses presented in Tables 15, 16, and 17 indicate that signal density appears to be the best stratification factor for arterial street within-route travel time variation. Average (approximately 50th percentile) c.v.'s are probably appropriate in calculating sample sizes for most travel time applications. For those travel time studies that require a high level of accuracy, use of the 85th percentile c.v. in sample size calculation may be more appropriate.

Table 23 shows suggested coefficients of variation for calculating the minimum number of travel time (or speed) runs on a particular arterial street section. It also contains illustrative sample size estimates for 80, 85, and 90 percent confidence levels with 10 percent relative error, and for 95 percent confidence with 5 percent relative error. The sample sizes are based on the normal distribution (Equation 20) and are about 2 observations less than equivalent estimates derived from a Student's *t* distribution.

Table 23 also suggests minimum sample sizes of 6 travel time runs for each arterial street segment to reflect the variability associated with individual drivers, random events, and lane choice, and which could have a disproportionate effect if encountered on one or two runs. This minimum is consistent with the recommendations of previous research.

Suggested Sample Size Estimates for Freeways. The stratification of freeway segments by ADT per lane and access frequency produce generally comparable coefficients of variation. However, the ADT per lane is more commonly found in roadway inventory bases and was used for estimating sample sizes. The average c.v.'s are probably appropriate for calculating sample sizes for most travel time applications. However, for those travel time studies that require a high level of accuracy, use of the 85th percentile c.v. in sample size calculation may be more appropriate.

TABLE 22 Reported approximate minimum sample sizes for 95 percent confidence level

Average Range in Travel Speed (mph)	Minimum Number of Runs for Specified Permitted Error				
	± 1.0 mph	± 2.0 mph	± 3.0 mph	± 4.0 mph	± 5.0 mph
2.5	4	2	2	2	2
5.0	8	4	3	2	2
10.0	21	8	5	4	3
15.0	38	14	8	6	5
20.0	59	21	12	8	6

Source: Reference (61).

TABLE 23 Suggested travel time variations and sample sizes on arterial streets

Signal Density Group	Average c.v. (%)	Minimum runs for 80%, 10%[a]	Minimum runs for 85%, 10%[b]	Minimum runs for 90%, 10%[c]	Minimum runs for 95%, 5%[d]
Low—less than 3 signals per mile	9	2(6)[e]	2(6)[e]	3(6)[e]	13
Medium—3 to 6 signals per mile	12	3(6)[e]	3(6)[e]	4(6)[e]	23
High—greater than 6 signals per mile	15	4(6)[e]	5(6)[e]	7	35

[a] 80% level of confidence, 10% relative error.
[b] 85% level of confidence, 10% relative error.
[c] 90% level of confidence, 10% relative error.
[d] 95% level of confidence, 5% relative error.
[e] Six runs needed to provide reasonable assurance that data are not affected by unusual conditions (e.g., driver behavior, signal malfunctions).

Note: Sample sizes calculated using Equation 20 (normal distribution). Use of Student's "t" distribution increases computed sample sizes by about 2 observations.

Table 24 shows suggested coefficients of variation and the associated sample sizes. Data are shown for 80, 85, and 90 percent confidence levels with 10 percent relative error, and 95 percent confidence with 5 percent relative error. A minimum of 5 travel time runs is recommended to ensure that the data are not unduly affected by unusual occurrences.

Data Collection Periods. The travel time runs should be conducted in each direction of travel during peak periods under good weather conditions. Because there can be pronounced variations within a peak period, it is essential that the required number of runs be representative of the peak period. At the same time, the minimum number of runs should be distributed over several different days of the week to ensure that representative data are collected. As a general guideline, no more than three to four runs should be obtained on any given day for each segment being analyzed.

Automatic traffic recorder stations should be used to help determine ideal days for data collection. Traffic volumes on Tuesdays, Wednesdays, and Thursdays are typically the most representative of average weekday traffic conditions. Therefore, the minimum number of runs should be obtained during these days. Additional runs beyond the minimum required may be obtained during Mondays or Fridays to gather comprehensive data about weekday traffic conditions.

TABLE 24 Suggested travel time variations and sample sizes on freeways

Signal Density Group	Average c.v. (%)	Minimum runs for 80%, 10%[a]	Minimum runs for 85%, 10%[b]	Minimum runs for 90%, 10%[c]	Minimum runs for 95%, 5%[d]
Low—less than 3 signals per mile	9	2(6)[e]	2(6)[e]	3(6)[e]	13
Medium—3 to 6 signals per mile	12	3(6)[e]	3(6)[e]	4(6)[e]	23
High—greater than 6 signals per mile	15	4(6)[e]	5(6)[e]	7	35

[a] 80% level of confidence, 10% relative error.
[b] 85% level of confidence, 10% relative error.
[c] 90% level of confidence, 10% relative error.
[d] 95% level of confidence, 5% relative error.
[e] Six runs needed to provide reasonable assurance that data are not affected by unusual conditions (e.g., driver behavior, signal malfunctions).

Note: Sample sizes calculated using Equation 20 (normal distribution). Use of Student's "t" distribution increases computed sample sizes by about 2 observations.

It may be desirable to measure free-flow speeds—those typically found at 10 a.m. or 10 p.m., for example. The minimum number of runs to obtain average free-flow speeds can be estimated by using coefficients of variation ranging from 5 percent to 8 percent. Alternatively, a minimum of 3 travel time runs should be performed in each direction for estimating free-flow speeds.

Sample Size Estimates for Roadway Segments

The number of roadway segments where travel times should be sampled can be estimated by Equations 22 and 23. These equations are easy to use and contain adjustments for finite populations. (However, for sample sizes of less than 30, they result in about 2 fewer observations than using the Student's t distribution.) Equation 23 should be used when the sample size accounts for more than 15 to 20 percent of the population.

$$\text{Sample Size}, n_o \cong \frac{z^2 c.v.^2}{e^2} \tag{22}$$

where

n_o = sample size (number of street segments) for an infinite population;
z = standard normal variate based on desired confidence level in the travel time estimate (two-tailed test);
$c.v.$ = spatial coefficient of variation of travel times (%); mean speed ÷ standard deviation, expressed as a percent; and
e = specified relative error (%), e.g., for ±10% error, 30 ± 3 min.

$$n = \frac{n_o}{1 + \frac{n_o}{N}} \tag{23}$$

where

n = finite population sample size, or number of street segments to sample in inventory;
n_o = sample size, infinite population (from Equation 23); and
N = population size, e.g., number of segments in inventory.

If, for example, there are only 40 arterial street segments in the roadway inventory, but Equation 22 calculated a sample size of 35 segments, the finite population sample size becomes much lower:

$$n = \frac{n_o}{1 + \frac{n_o}{N}} = \frac{35}{1 + \frac{35}{40}} = 19 \ segments$$

Arterial Streets. Table 25 provides between-route coefficient of variation (c.v.) values for arterial streets stratified by arterial class. The 1994 HCM (*8*) defines three separate arterial classes based upon design characteristics, free-flow speed, posted speed limits, relative access, and signal density. The variation for the arterial classes ranges from 20 percent to 25 percent. Sample size estimates are based on Equation 22. They should be reduced by Equation 23 to reflect the number of street segments in a particular strata group.

Freeways. Table 26 provides between-route coefficient of variation (c.v.) values for freeways stratified by average daily traffic volume per lane. Illustrative sample sizes are also provided in Table 26 by using Equation 22. The sample sizes should be reduced using Equation 23 according to the number of street segments in the particular strata.

Additional Considerations. There may be segments in an urban area that experience serious recurrent congestion. It

TABLE 25 Suggested values of between-route variability for arterial streets and illustrative sample sizes

Arterial Class	Average c.v. (%)	Minimum Number of Segments for 80%, 10%[a]	Minimum Number of Segments for 85%, 10%[b]	Minimum Number of Segments for 90%, 10%[c]	Minimum Number of Segments for 95%, 5%[d]
Class I	20	7	9	11	62
Class II	23	9	11	15	82
Class III	25	11	13	17	96

[a] 80% level of confidence, 10% relative error.
[b] 85% level of confidence, 5% relative error.
[c] 90% level of confidence, 10% relative error.
[d] 95% level of confidence, 5% relative error.

Note: Minimum number of segments calculated using Equation 22. Samples should be reduced by finite segment equation (Eq.23). Where the sample size is under 30, two additional observations could be added to reflect non-abnormality in the distribution of sample means.

TABLE 26 Suggested values of between-route variability for freeways and illustrative sample sizes

ADT per Lane Range	Average c.v. (%)	Minimum Number of Segments for 80%, 10%[a]	Minimum Number of Segments for 85%, 10%[b]	Minimum Number of Segments for 90%, 10%[c]	Minimum Number of Segments for 95%, 5%[d]
Low—Less than 15,000 ADT per lane	15	4	5	7	35
Medium—15,000 to 20,000 ADT per lane	20	7	9	11	62
High—Greater than 20,000 ADT per lane	25	11	13	17	96

[a] 80% level of confidence, 10% relative error.
[b] 85% level of confidence, 10% relative error.
[c] 90% level of confidence, 10% relative error.
[d] 95% level of confidence, 5% relative error.

Note: Minimum number of segments calculated using Equation 22. Samples should be reduced by finite segment equation (Eq. 23). Where the sample size is under 30, two additional observations could be added to reflect non-abnormality in the distribution of sample means.

may be desirable to also measure speeds on these segments if they were not already included in the sample. The frequency of data collection efforts, or monitoring of congestion, depends upon traffic volume growth on the regional network and current levels of service. If traffic volume is high and many roadways exhibit a poor level of service, monitoring efforts should be conducted every one to two years. In areas of moderate traffic volume growth and acceptable levels of service, monitoring may be necessary every two to three years. Local conditions like extensive roadway construction may alter the data collection schedules. The frequency of data collection may also rely on budgeting and programming criteria.

Vehicle Occupancy Counts

Traffic classification counts often obtain information on vehicle type, including buses, taxis, trucks, single-occupant vehicles, carpools, and vanpools. Vehicle occupancies are obtained in cordon counts around major activity centers, or as part of regular planning and monitoring studies. Vehicle occupancy counts are not usually measured when traffic counts are made.

Historically, statistical analyses of vehicle occupancy data have employed simple random sampling. However, stratified sampling procedures can also be used. The *FHWA Guide for Estimating Urban Vehicle Classification and Occupancy* (*62*) contains detailed descriptions of both types of sampling and basic pressures of variation. Table 27 contains the reported standard deviations of average vehicle (automobile) occupancy.

The sample size of "link days" needed to estimate average vehicle occupancy within a desired tolerance can be estimated by the following equation:

$$N_1 = \frac{Z^2 S^2}{E^2} \tag{24}$$

TABLE 27 Standard deviations of average occupancy

Source of Variation	Symbol	Ranges	Recommended Value	Location(s)
Location/Day	S_1	.057-.069	.063	1,2
Day	S_2	.005-.028	.015	1
Season	S_3	.011-.019	.015	3,4
Within Day	S_4	.012-.022	.017	2,5

Locations:
1 Killeen-Temple, Texas
2 Seattle, Washington
3 Minneapolis, Minnesota
4 Albany, New York
5 Washington, D.C.

Source: Ref. (62)

where

Z = standard normal variate based on desired confidence level,
E = allowable (absolute) error or tolerance,
S = composite deviation of average occupancy, and
N_1 = number of link-days needed.

$$S = S_1^2 + S_3^2 + S_4^2 \quad (25)$$

where

S_1 = standard deviation of average occupancy across link-days within a season,
S_3 = standard deviation across seasons, and
S_4 = standard deviation across time periods during a day as a result of short counts.

Analysis in which the locations are fixed leads to the following equation

$$N_2 = \frac{Z^2 S^2}{E^2} \quad (24a)$$

where

N_2 = number of days of data collection, and

$$S^2 = S_2^2 + S_3^2 + S_4^2 \quad (25a)$$

where

S_2 = standard deviation of average occupancy across days of a single season,
S_3 = standard deviation across seasons, and
S_4 = standard deviation across time periods during a day as a result of short counts.

In practice, it is necessary to sample each type of vehicle at a location separately, especially buses versus cars. This type of stratification is necessary in corridors with public transport and/or preferential facilities for high-occupancy vehicles.

Agencies may wish to consider the applicability of stratified sampling to their occupancy data collection. This may not be a major concern for corridors without priority treatment or areas without policies that support ridesharing or transit. It may also not be a factor in cases where the count is conducted on a high-occupancy vehicle facility and the total number of vehicles and persons are being counted directly by observation. There are many other cases, including areawide, subarea, and job site studies which may benefit from a stratification of the sampling plan.

The variance of the overall estimate of vehicle occupancy obtained through the application of a stratified random sample should be smaller than that obtained using a simple random sample. The only additional cost to the evaluation process is the necessity of recording vehicle type, as well as occupancy, for each vehicle in the sample. Since vehicles are normally classified to determine utilization and occupancy levels by mode, this approach should not present additional cost to the evaluation process.

The selection of the sample, in hours, days, and locations, needs careful planning. It is important to remember that the sample intervals, each of which is a specified time interval at a particular location, must be randomly selected from the total population (defined as the collection of units from which the sample is drawn). In other words, all locations and time periods that the estimated average vehicle occupancy is to represent must be included in the defined population, and the sample intervals must be randomly chosen from that population. For instance, if an estimate of vehicle occupancy is needed for the weekday peak period during the summer months, the sampling frame would consist of all morning and evening peak periods on all weekdays for the months of June, July, and August. Each peak period interval would, therefore, be a sampling unit.

The selection of intervals for sampling should be done randomly, with all peak-period intervals on weekdays during the three months having equal probability of being chosen. The number of intervals in the sample would be determined by the standard errors, for specified sample sizes using stratified random sampling, and from knowledge of the volume expected during one interval. The standard deviations in vehicle occupancies obtained from data collection on the Houston HOV lane system (*63*) were 0.5, 2.5, and 10.0 persons per vehicle for cars, vans, and buses, respectively. Due to the limited range of vehicle occupancies for each vehicle type, large deviations from these values are not expected. This approach could also be extended to include commercial vehicles.

Use of a stratified sample plan could provide information on vehicle occupancies sufficient to allow the results of most vehicle-based analysis procedures to be expressed in person-volume terms. This not only improves the transferability of the information, but also emphasizes the concept of transportation systems to move people.

SURROGATE ESTIMATION PROCEDURES

There are many situations in which it is not practical to make detailed travel time surveys or to use various HCM procedures to measure congestion. Examples include regional policy assessments, forecasts of future route or area performance, or determining the impacts of adding or removing traffic control signals. Cost and person-hour constraints may also make detailed surveys impractical—especially where a large area must be assessed.

In such cases, surrogate estimating procedures can play an important role. These procedures use readily available data when direct data collection is not feasible. The following sections discuss the analyses that were performed to develop surrogate travel time/speed estimating procedures. They build upon and extend previous work.

Arterial Streets

Literature Review. A review of the literature indicated several variables could be used to estimate speeds. These variables include signal density, traffic volumes, percent green for through movements, signal coordination, and speed limit. The following paragraphs provide a brief summary of previous research in estimating speeds on arterial streets.

Treadway and Oppenlander (*64*) developed statistical models that could be used to estimate travel speeds and delays on high-volume highways. A multiple linear regression analysis was performed to gauge the effects of various traffic and roadway characteristics on travel speeds. The results of the study indicated that approximately 50 percent of the variation in speed on uninterrupted flow sections was explained by five variables, namely, street intersections per mile, commercial establishments per mile, percent of sections where passing was not permitted, practical capacity, and traffic volume. Treadway and Oppenlander concluded that the most significant factors to consider in estimating travel speeds were the types of roadside development (e.g., commercial, urban, or rural) and the traffic stream friction (e.g., traffic volumes and practical capacity).

Coleman (*43*) documented the effect of location and street type, heavy commercial vehicles, street width, signal coordination and density, and traffic volumes on the travel times along 15 test sections in five cities in Pennsylvania. Of all factors examined, Coleman found that travel rate (in minutes per mile) best correlated with signal density (signals per mile) when stratified by peak-hour volume-to-capacity (v/c) ratios for traffic flows less than critical density. For Coleman's relationships, the coefficients of correlation (r) for the v/c ratio ranges varied from 0.75 to 1.0, indicating that between 56 percent and 100 percent of the travel time variability can be explained through the empirical equations (using R^2 value). Area type, location, street type and width, percentage of heavy commercial vehicles, and signal coordination were found to have little to no correlation (coefficients of correlation ranging from 0.01 to 0.52) to travel times.

Guinn (*65*) conducted a similar evaluation on 77 street sections in New York State in 1967 to determine the relative effects of several parameters on travel times on urban streets. The study used the test vehicle method to collect travel times and other roadway and control characteristics, including number of lanes, speed limit, number of signals, percent green time of each signal, section length, link and area type, parking, and number of intersections, for each of the 77 sections. A multiparameter analysis was performed to test the significance of each of the parameters.

Guinn concluded that neither a multiple-parameter nor a single-parameter estimating equation could be developed that would explain the variation in travel times for urban streets. The empirical analysis did indicate, however, that signal density was the most important parameter affecting speeds on urban streets. The recommendations suggested that three parameters, namely, signal density, traffic volume per lane, and speed limit, should be included in any further analytical studies of travel times on urban streets.

Civgin (*66*) considered the effects of posted speed limits, presence of a dividing median, v/c ratio, surface condition rating, number of lanes, traffic volume, parking, and practical capacity on travel times. The study used a multiple regression analysis. The coefficient of determination (R^2 = 0.05) indicated a weak linear correlation between average travel speed and the independent variables, with less than 5 percent of the travel time variation explained by the independent variables. Civgin noted that posted speed limits and the v/c ratio had the greatest effect on average travel speeds, and other variables like surface condition rating and parking had little to no effect on average travel speed.

A study of travel times in the New Haven, Connecticut, area found that signal density had a major influence on speeds (*67*). Signal density alone explained 50 percent of the variance while the number of vehicles per lane per hour alone explained only 4 percent of the variance. The multiple correlation coefficient between speed and these variables was 0.71. The resulting equation was

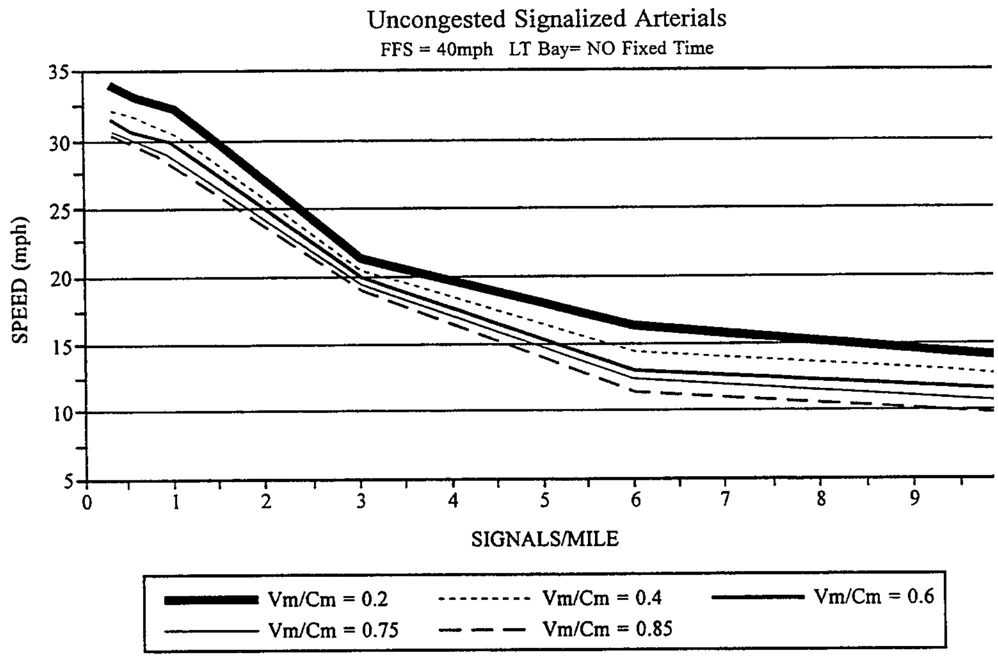
$$\begin{array}{l}\textit{Peak-Hour}\\ \textit{Travel Speed}\\ (\textit{mph})\end{array} = 34.35 - \left(0.006 \times \begin{array}{c}\textit{Peak-Hour}\\ \textit{Lane Volume}\end{array}\right) - 2.265\ (\textit{Signal Density}) \tag{26}$$

Ewing (*68*) suggested a simple linear model for average travel speed based on two independent variables: peak-hour traffic volume and signal density (Equation 27). The model was based on 17 two-lane streets in Seminole County, Florida, and included data for the morning and evening peak hours in both directions (68 total observations). Ewing noted that although the explanatory power of this model was probably inadequate (R^2 =0.55) for determining roadway levels of service, a better predictive model could be developed with more variables like the green ratio, arrival type, and percentage of turns from exclusive lanes.

$$\begin{array}{l}\textit{Average}\\ \textit{Travel Speed}\\ (\textit{mph})\end{array} = 44.7 - \left(0.0087 \times \begin{array}{c}\textit{Peak-Hour}\\ \textit{Traffic Volume}\end{array}\right) - \left(7.74 \times \begin{array}{c}\textit{Signals}\\ \textit{Per Mile}\end{array}\right) \tag{27}$$

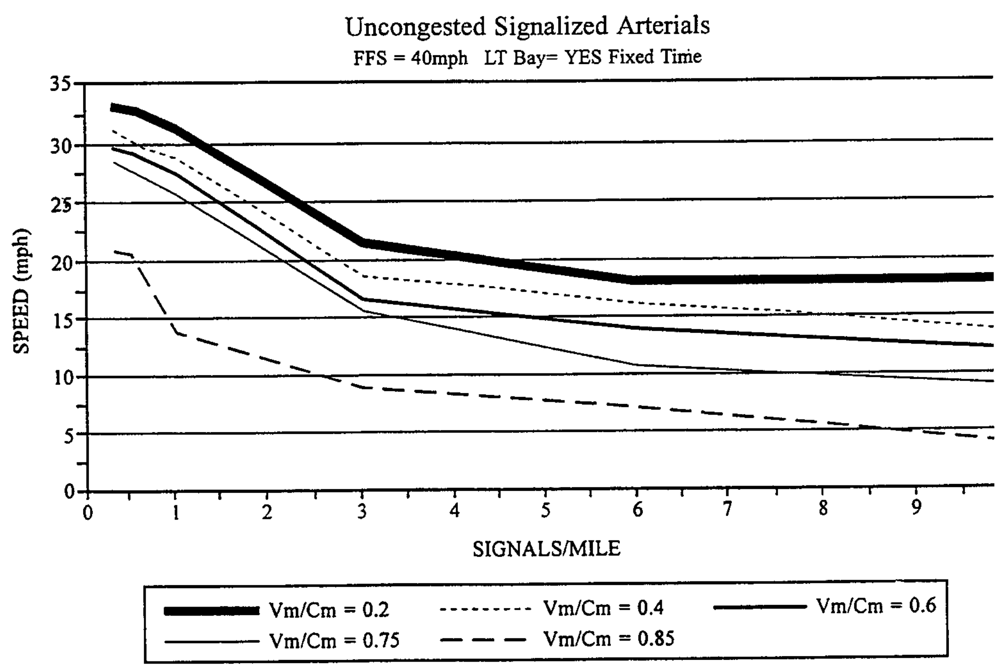
Margiotta et al. (*69*) used the computer model NETSIM to simulate the effects of signal density and volume-to-capacity ratios on average travel speed. This study found that signal density had one of the greatest effects on travel speed, as illustrated in Figures 7 and 8. The study also concluded that signal progression was a significant variable.

In summary, a number of attempts have been made to estimate travel speed or time based on traffic, roadway, or control characteristics. With the exception of Coleman's research (which was based on a limited data set), most of the models that have been developed to estimate travel speed account for less than 60 percent of the observed variability. There is a gen-



Source: Reference 69

Figure 7. NETSIM results for signal density versus speed: Uncongested arterials with no left turn bays.



Source: Reference 69

Figure 8. NETSIM results for signal density versus speed: Uncongested arterials with left turn bays.

eral consensus, however, about the independent variables most directly related to travel time and speed. These variables include traffic volumes and/or roadway capacity ratios (e.g., v/c ratio or volume per lane), signal density, and character of the roadway (e.g., roadside development, access, or speed limit). Practically all research of empirical relationships in the literature concentrated on arterial streets with little or no emphasis on freeways or uninterrupted flow.

Surrogate Development. Surrogate relationships were derived, drawing upon the results of previous studies and an initial analysis of the data collected. The steps were as follows:

The following variables were found to closely relate to travel speeds:

- Signal density,
- Traffic volume (average daily traffic or ADT) per lane (a surrogate for volume-to-capacity ratio), and
- Percent green for through movement.

A conceptual model (Equation 28) was developed that attempted to relate these variables to the components of delay that are typically experienced along an arterial street. For instance, travel time delay due to stops at signals is probably related to the signal density.

$$\begin{aligned} \textit{Travel speed} = {} & \begin{matrix}\textit{Free-Flow}\\ \textit{Speed}\end{matrix} - \begin{matrix}\textit{Acceleration/Deceleration}\\ \textit{Delay at Signals}\end{matrix} \\ & - \begin{matrix}\textit{Delay Time}\\ \textit{at Signals}\end{matrix} - \begin{matrix}\textit{Delay in}\\ \textit{Queuing}\end{matrix} \end{aligned} \tag{28}$$

$$\begin{aligned} \textit{Travel speed} = {} & \begin{matrix}\textit{Free-Flow}\\ \textit{Speed}\end{matrix} - [\textit{Signals/Mile}] \\ & - [\textit{Signals/Mile} \times \%\ \textit{Red}] \\ & - [\textit{ADT/Lane} \times \%\ \textit{Green}] \end{aligned} \tag{28a}$$

A simpler form of Equation 28 was constructed to test the differences between an equation with many input variables and an equation with few variables (Equation 29).

$$\begin{aligned} \textit{Travel Speed} = {} & \textit{Constant Based on Free-Flow Speed} \\ & - \textit{Signal Density} - \textit{ADT/Lane} \end{aligned} \tag{29}$$

The results of this comparison for the data sets from different cities are shown in Table 28. Two variables—R^2 and root mean square error—were used to quantify the relative significance of the two different equations. The R^2 value, or coefficient of determination, represents the portion of variability that can be explained by a model. An R^2 value of 1.0 represents a perfect fit of empirical data to a regression model. The mean square error is a relative measure of the error for a particular model and is used in sample size and confidence interval calculations.

TABLE 28 Comparison of two different regression models

City	Number of Segments	Equation 29		Equation 30	
		R-squared	Root Mean Square Error	R-squared	Root Mean Square Error
Bristol, TN/VA	18	0.39	5.65	0.41	4.94
Chicago, IL	94	0.43	8.64	--[a]	--
Connecticut	20	0.05	6.62	0.08	6.54
Champaign-Urbana, IL	264	0.13	6.93	--[a]	--
DuPage County, IL	1,159	0.07	13.85	--[a]	--
Indianapolis, IN	305	0.29	7.15	--[a]	--
Massachusetts	30	0.22	9.27	0.25	8.13
Maryland	8	0.76	4.25	--[a]	--
Memphis, TN	24	0.25	4.19	0.44	3.65
MWCOG	22	0.22	8.69	--[a]	--
North Carolina	18	0.80	6.56	--[a]	--
Ohio	253	0.29	7.87	0.30	7.86
Springfield, MO	20	0.02	5.56	0.14	5.27

[a] Data not available for % green.

The more complex model, based on the information analyzed, did not perform better than the simpler model. More significantly, the data showed relatively low R^2 values in many cities.

Several factors explained the low R^2 values. In Connecticut, for example, signals were widely spaced along roads with good progression. In DuPage County, roadway sections were extremely short—a situation prevalent in several other urban areas as well. Finally, the aggregate data did not account for the differing free-flow speeds on various classes of roadway.

Based on Table 28, it was concluded that a simple model with few variables (Equation 29) could provide nearly the same error level as a more complex, conceptually sound model (Equation 28) and that the data should be further stratified.

Using PC-SAS, an equation was formulated for all arterial streets in the database (2,231 street segments). The following equation and statistics were obtained:

$$\underset{(mph)}{Average\ Speed} = 35.1 - 0.255\left(\frac{ADT/Lane}{1000s}\right) - 1.35\,(Signal\ Density) \qquad (30)$$

$$R^2 = 0.14$$
$$\text{Root mean square error} = 10.14$$
$$\text{c.v.} = 35\%$$

The mean square error is relatively high (wide confidence interval) and the R^2 value is also low, indicating a significant amount of unexplained variability. It was decided to stratify the arterial segments by arterial class (as defined by the 1994 *Highway Capacity Manual*) and look at the data on a city-by-city basis.

Regression coefficients were obtained for the following general equation on a city-by-city basis for each arterial class:

$$\underset{(mph)}{Average\ Speed} = [Intercept] - \begin{bmatrix} ADT\ per\ Lane \\ (1000s) \\ Coefficient \end{bmatrix}\left(\frac{ADT/Lane}{1000s}\right) - \begin{bmatrix} Signal \\ Density \\ Coefficient \end{bmatrix}\left(\begin{matrix} Signal \\ Density \end{matrix}\right) \qquad (31)$$

The results for these regression analyses are contained in Tables 29–31 for Arterial Classes I, II, and III. From these tables, it became obvious that data from several of the cities were not providing reasonable results. For example, the data for Class I arterials from North Carolina gave coefficients that were drastically different from the other cities. In cases like this, the data set producing unreasonable regression results was removed and the regression analyses were performed again. Data with extremely high error values were also removed.

For each arterial class, the following cities' data were removed:

Class I Arterial Data Removed:
- Chicago, Illinois
- DuPage County, Illinois
- North Carolina
- Springfield, Missouri

Class II Arterial Data Removed:
- Bristol, Tennessee/Virginia
- DuPage County, Illinois

TABLE 29 Regression of Class I arterials

City	Number of Segments	Intercept	ADT per Lane (1000s) Coefficient	Signal Density Coefficient	R-squared	Root Mean Square Error
Bristol	7	45.0	-0.57	-7.11	0.55	3.8
Chicago	39	39.6	-0.28	-0.77	0.01	8.56
Connecticut	19	40.5	-0.28	-2.26	0.12	5.25
DuPage County	964	34.7	-0.24	-1.14	0.11	10.00
Indianapolis	199	35.8	-1.37	-2.52	0.38	6.50
Memphis	9	47.5	-0.63	-5.82	0.77	1.87
MWCOG	4	42.4	-0.43	-2.45	0.64	7.17
North Carolina	5	111.0	-12.0	-12.30	0.92	4.67
Ohio	89	36.1	+0.30	-3.53	0.42	6.25
Springfield	3	-37.0	+4.00	+6.29	0.76	2.23

TABLE 30 Regression of Class II arterials

City	Number of Segments	Intercept	ADT per Lane (1000) Coefficient	Signal Density Coefficient	R-squared	Root Mean Square Error
Bristol	7	24.2	+0.42	-1.38	0.77	2.30
Chicago	41	32.9	-0.40	-2.53	0.16	5.66
Champaign-Urbana	93	36.6	-0.28	-0.86	0.13	6.13
DuPage County	183	35.5	-0.74	-1.11	0.04	20.00
Indianapolis	89	26.1	-1.69	-0.82	0.20	5.40
Massachusetts	13	34.1	-0.20	-2.53	0.41	5.05
Memphis	13	34.8	-0.08	-1.68	0.10	3.50
North Carolina	7	46.2	-0.63	-7.30	0.99	1.40
Ohio	49	27.2	-0.60	-1.73	0.22	6.42
Springfield	15	29.6	-0.02	-1.43	0.06	4.89

Class III Arterial Data Removed:
Chicago, Illinois
DuPage County, Illinois

Once the cities' data were removed from the analysis, regression was performed again for the three arterial classes by combining information from the test cities. The following equations and statistics were obtained:

Class I Arterials

$$\underset{(mph)}{Avg.\ Speed} = 40.6 - 0.20(ADT/Lane\ 1000s) - 2.67 \times (Signals/Mile) \tag{32}$$

$R^2 = 0.35$
Root mean square error = 6.59
c.v. = 20%

Class II Arterials

$$\underset{(mph)}{Avg.\ Speed} = 33.1 - 0.35(ADT/Lane\ 1000s) - 0.73 \times (Signals/Mile) \tag{33}$$

$R^2 = 0.07$
Root mean square error = 6.23
c.v. = 21%

TABLE 31 Regression of Class III arterials

City	Number of Segments	Intercept	ADT per Lane (1000) Coefficient	Signal Density Coefficient	R-squared	Root Mean Square Error
Chicago	11	13.0	-0.11	-0.02	0.02	2.00
Champaign-Urbana	169	33.0	-0.13	-0.69	0.30	6.13
DuPage County	9	42.0	-4.0	-0.32	0.02	12.90
Indianapolis	13	28.5	-0.52	-0.26	0.06	4.22
Massachusetts	9	41.0	-1.21	-3.75	0.77	3.62
MWCOG	11	24.9	-0.56	-1.60	0.44	5.26
Ohio	11	27.8	-0.07	-1.28	0.33	7.84

Class III Arterials

$$\begin{aligned} \mathit{Avg.\ Speed\ (mph)} &= 32.2 - 0.55(\mathit{ADT/Lane}\ 1000s) \\ &\quad - 0.79 \times (\mathit{Signals/Mile}) \end{aligned} \tag{34}$$

$$\begin{aligned} R^2 &= 0.23 \\ \text{Root mean square error} &= 5.84 \\ \text{c.v.} &= 23\% \end{aligned}$$

The equation coefficients for Class II and Class III arterials were similar, so the two data sets were combined and an equation was developed for *both* Class II and Class III arterials together. The equation is as follows:

Class II and Class III Arterials Combined

$$\begin{aligned} \mathit{Average\ Speed\ (mph)} &= 36.4 - 0.301(\mathit{ADT/Lane}\ 1000s) \\ &\quad - 1.56\ (\mathit{Signals/Mile}) \end{aligned} \tag{35}$$

$$\begin{aligned} R^2 &= 0.28 \\ \text{Root mean square error} &= 7.39 \\ \text{c.v.} &= 25\% \end{aligned}$$

Once average speeds have been calculated, travel times and travel rates can be easily calculated using the following equations:

$$\mathit{Travel\ Time\ (minutes)} = \frac{60 \times \mathit{Segment\ Length\ (miles)}}{\mathit{Average\ Speed\ (mph)}} \tag{36}$$

$$\mathit{Travel\ Rate\ (minutes\ per\ mile)} = \frac{60}{\mathit{Average\ Speed\ (mph)}} \tag{37}$$

These equations may be used to estimate average speeds for arterial street sections. Of equal importance is the confidence interval or prediction interval associated with the estimated speed. The confidence interval (Equation 38) is used when an average value of speed for a particular street segment is desired. For example, the average speed is estimated because no direct data collection was possible. The confidence interval would be used for this application. The prediction interval (Equation 39) is used when we wish to predict the *actual* speed for a *particular* travel time run (not commonly done in practice). The prediction interval is considerably wider than the confidence interval because it is based on the prediction of a specific speed value, not an average speed value.

$$\begin{aligned} &\mathit{Confidence\ Interval} \\ &\quad = (t_{\alpha,n-1})(\mathit{Root\ Mean\ Square\ Error})(\sqrt{1/n}) \end{aligned} \tag{38}$$

$$\begin{aligned} &\mathit{Prediction\ Interval} \\ &\quad = (t_{\alpha,n-1})(\mathit{Root\ Mean\ Square\ Error})(\sqrt{1 + 1/n}) \end{aligned} \tag{39}$$

where $t_{\alpha,n-1}$ equals t-value based on desired confidence level and n equals sample size from regression equation. Note that when $n \geq 30$, use Z and the standard normal distribution.

As an example, we wish to estimate the average speed for a Class I arterial with an ADT/lane of 5,000 and signal density of 3 signals per mile. We have the following:

$$\begin{aligned} \mathit{Average\ Speed\ (mph)} &= 40.6 - 0.20(5) - 2.67(3) \\ \mathit{Average\ Speed} &= 32 \text{ mph} \\ n &= 300 \end{aligned}$$

The 95 percent confidence interval associated with this estimated speed is

$$\mathit{Confidence\ Interval} = (1.96)(6.59)(\sqrt{1/300}) = 0.75\ \mathit{mph}$$

So, we can say with 95 percent confidence the following:

$$\mathit{Average\ Speed} = 32 \pm 0.75\ \mathit{mph}$$

To predict an individual speed run, the average speed is the same and the 95 percent prediction interval is

$$\mathit{Prediction\ Interval} = (1.96)(6.59)(\sqrt{1 + 1/300}) = 12.9\ \mathit{mph}$$

The prediction interval is rather large because it contains two sources of error: between-route variation and within-route variation. The confidence interval contains only between-route variation; the confidence interval is much lower than the prediction interval.

The following conclusions can be drawn from the equations obtained through the multiple linear regression analyses:

- Stratification (e.g., by arterial class) appears to reduce model error. Arterial class is consistent with current 1994 HCM level-of-service standards and served as a useful stratification factor. Other variables like ADT per lane or signal density could be used; however, this analysis showed that grouping by arterial class provided the largest reduction in model error.
- Signal density is the most important factor in estimating average speeds on arterial streets. This finding is consistent with previous research on estimating speeds on arterial streets. The values of the signal density coefficients in the regression equations are similar to those obtained by other travel time estimation studies (Figure 9). The ADT per lane value is considerably less important than signal density in estimating arterial street speeds when roads operate below capacity.
- The R^2-values indicate that a large portion of the data variability (70–85 percent) is not explained by the model. The mean square error and c.v. values, however,

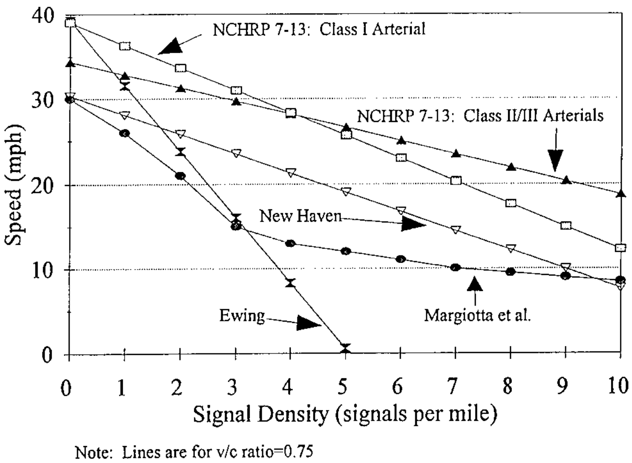


Figure 9. Comparison of arterial street speed prediction models.

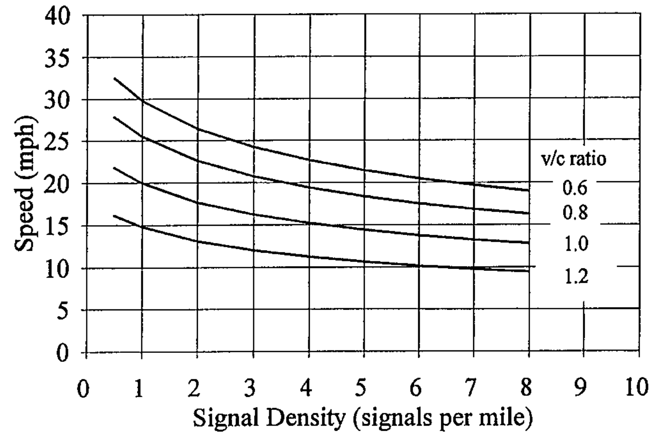


Figure 10. Suggested speed estimation curves for Class I arterials using v/c ratio.

are consistent with the values associated with direct sampling of travel times.

- Some of the input data used relatively short sections that magnify the signal density parameters and may give misleading results where relatively few speed runs were made. Much of the data using short sections were eliminated from the statistical analyses.
- The regression equation coefficients varied from city to city, indicating a difference in operating conditions for the street segments within the same arterial class. The regression equations (Equations 33 through 36) represent average conditions for medium to large cities across the United States.
- The effects of signal progression—through bandwidth and progressive speed—were not explicitly considered. Very few agencies were able to submit data on the quality of progression for unknown reasons.

Further Comparisons. A comparison of the NCHRP arterial equations (Equations 32 and 35) and other arterial street speed prediction models are shown in Figure 9 for similar traffic volumes. The slope of the two NCHRP lines are in general agreement with the Margiotta and New Haven curves. However, the NCHRP lines provide higher speeds for most signal densities. The NCHRP equations for Class I and Classes II and III also cross each other at 4 signals per mile, an anomaly that could not be explained in the data analysis. The slope of the Ewing curve is similar to Margiotta's for low signal densities, but provides unreasonable results for signal densities greater than 4 signals per mile. Ewing's data only included two-lane minor arterials, which could explain poor prediction at high signal densities. The nonlinearity of Margiotta's Curve is consistent with current speed relationships and research and may explain the low correlations in the linear models tested.

Suggested Relationships. Composite curves, based on the curves and lines in Figure 9, were constructed with the desirable features of each different curve/line taken into consideration. The composite curves, shown in Figures 10 through 13, show a non-linear relationship between signal density and average speed for the various traffic volume levels. For low signal densities (less than three or four signals per mile) and low traffic volumes, signal density is the overriding factor in determining average speeds. For high traffic volumes (v/c greater than 1.0, ADT/lane greater than 8,000 to 10,000), the traffic volume has a greater effect than signal density on average speed. The results of the NCHRP analysis also indicated that Class I arterials have higher average speeds than Class II or III arterials for comparable traffic volume levels or signal densities.

The curves in Figures 10 through 13 are suggested for estimating speeds on arterial streets for different traffic volume levels and signal densities. Equations 40, 41, and 42 were derived from the curves shown in Figures 10 through 13. The equations incorporate the major variables from these figures: v/c ratio (or ADT/Lane), signal density, and free-flow speeds. Tables 32 and 33 show the speed estimation curves in a tabular format. Although these curves are different than

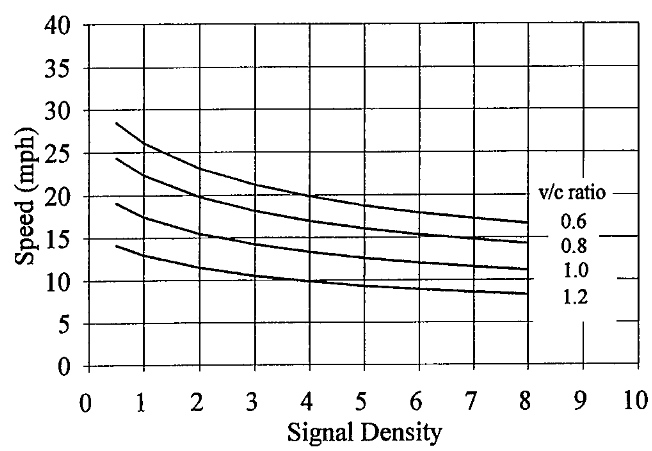


Figure 11. Suggested speed estimation curves for Class II and III arterials using v/c ratio.

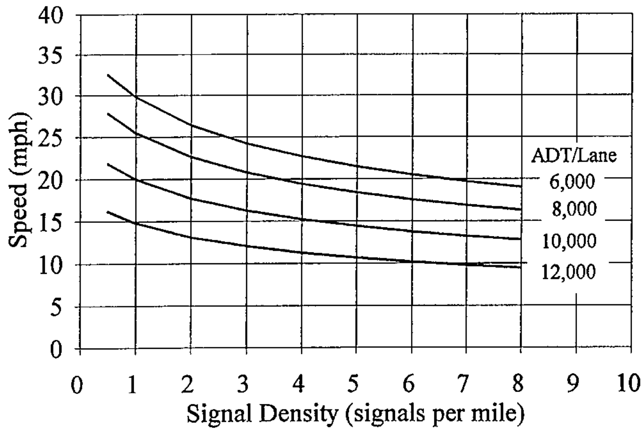


Figure 12. Suggested speed estimation curves for Class I arterials using ADT/lane.

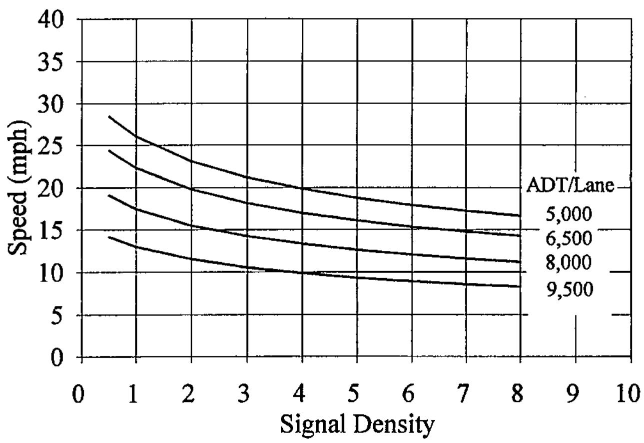


Figure 13. Suggested speed estimation curves for Class II and III arterials using ADT/lane.

those specific equations (Equations 32 and 35) developed from the NCHRP data, the suggested curves are more consistent with several other studies and remove several anomalies and unexplained problems with the NCHRP data. The suggested curves provide results that are intuitively correct and correspond to current methods of estimating speeds on other types of facilities.

The curves in Figures 10 through 13 indicate the following:

- Traffic signal density has a greater effect than traffic volumes on reducing speeds when traffic volumes are less than capacity. Signals have their greatest reductive effect when they are introduced into free-flowing or lightly interrupted traffic (from 0 to 3 signals per mile) (0 to 2 signals per kilometer).
- When traffic volumes approach, or exceed capacity, there is a considerable drop in speeds at all signal densities.
- Signal progression can be introduced into the curves by viewing the signal density in terms of "effective" signals per mile. The effective signals per mile equals the product of (1-bandwidth/cycle length) and the signals per mile. For example, a 40 percent through band would result in 60 percent of the signal density associated with little or no progression.

The curves provide reasonable approximations for planning and policy purposes. They can be used to assess the impact of adding traffic volumes and/or traffic signals to a given roadway.

All Arterials. Using the Volume-to-Capacity Ratio

$$\begin{matrix}\textit{Peak-}\\\textit{Hour}\\\textit{Speed}\\(\textit{mph})\end{matrix} = \frac{60}{\left(\dfrac{60}{\begin{matrix}\textit{Free-}\\\textit{Flow}\\\textit{Speed}\\(\textit{mph})\end{matrix}}\right)\left(1+\begin{matrix}\textit{Effective}\\\textit{Signal}\\\textit{Density}\end{matrix}\right)^{0.3}\left[1+(v/c)^4\right]^{0.7}} \tag{40}$$

where v/c equals volume-to-capacity ratio.

Class I Arterials. Using ADT/Lane as a Surrogate for the v/c Ratio

$$\begin{matrix}\textit{Peak-}\\\textit{Hour}\\\textit{Speed}\\(\textit{mph})\end{matrix} = \frac{60}{\left(\dfrac{60}{\begin{matrix}\textit{Free-}\\\textit{Flow}\\\textit{Speed}\\(\textit{mph})\end{matrix}}\right)\left(1+\begin{matrix}\textit{Effective}\\\textit{Signal}\\\textit{Density}\end{matrix}\right)^{0.3}\left[1+\left(\dfrac{\textit{ADT/ Lane}}{10,000}\right)^4\right]^{0.7}} \tag{41}$$

Class II/III Arterials. Using ADT/Lane as a Surrogate for the v/c Ratio

$$\begin{matrix}\textit{Peak-}\\\textit{Hour}\\\textit{Speed}\\(\textit{mph})\end{matrix} = \frac{60}{\left(\dfrac{60}{\begin{matrix}\textit{Free-}\\\textit{Flow}\\\textit{Speed}\\(\textit{mph})\end{matrix}}\right)\left(1+\begin{matrix}\textit{Effective}\\\textit{Signal}\\\textit{Density}\end{matrix}\right)^{0.3}\left[1+\left(\dfrac{\textit{ADT/ Lane}}{8,000}\right)^4\right]^{0.7}} \tag{42}$$

TABLE 32 Suggested speed estimation table for Class I arterials

Signal Density (signals per mile)	Average Speed (mph) for ADT/Lane or v/c Ratio			
	6,000[1]	8,000[1]	10,000[1]	12,000[1]
	0.6[2]	0.8[2]	1.0[2]	1.2[2]
0.5	33	28	22	16
1	30	26	20	15
2	26	23	18	13
3	24	21	16	12
4	23	19	15	11
5	21	18	14	11
6	20	18	14	10
7	20	17	13	10
8	19	16	13	9

[1] ADT per lane
[2] v/c ratio
Note: Assumed free-flow speed of 40 mph.

Once average speeds have been calculated, travel times and travel rates can be easily calculated using the following equations:

$$\begin{matrix}\mathit{Travel\ Time}\\ \mathit{(minutes)}\end{matrix} = \frac{60 \times \mathit{Segment\ Length\ (miles)}}{\mathit{Avg.\ Speed\ (mph)}} \tag{43}$$

$$\begin{matrix}\mathit{Travel\ Rate}\\ \mathit{(minutes\ per\ mile)}\end{matrix} = \frac{60}{\mathit{Avg.\ Speed\ (mph)}} \tag{44}$$

Freeways

There are several computer models and simulation packages that currently can be used to estimate average freeway speeds. However, these models typically rely on detailed traffic volume and geometric data that may not be readily accessible or available to planning agencies in small urban areas, or be suitable for future projections and analyses. Therefore, the freeway analysis, like that for arterial streets, attempted to develop simple regression equations to predict average travel speeds.

Preliminary analyses indicated that ADT per lane and access frequency (number of access points per mile) were the variables most closely related to average freeway speeds. The effects of geometric or other bottlenecks on upstream sections were noted as a potential problem for any simple model. For example, vehicle queues could extend several miles upstream of a bottleneck, consequently lowering speeds on a section with low ADT per lane and access frequency values. Accordingly, several "conceptual" techniques were developed to help account for the effects of bottlenecks on upstream freeway sections. These techniques modified ADT per lane values to account for any downstream queuing that could extend upstream into the study section.

"Transposed" Volumes. The first conceptual technique was simply "transposing" or sliding ADT per lane values to the next adjacent upstream section. This technique assumes that the ADT per lane value in the adjacent downstream section is a better estimate of speed than the actual ADT per lane value. This technique was only used for sections in which the

TABLE 33 Suggested speed estimation table for Class II/III arterials

Signal Density (signals per mile)	Average Speed (mph) for ADT/Lane or v/c Ratio			
	6,000[1]	8,000[1]	10,000[1]	12,000[1]
	0.6[2]	0.8[2]	1.0[2]	1.2[2]
0.5	28	24	19	14
1	26	22	18	13
2	23	20	15	11
3	21	18	14	11
4	20	17	13	10
5	19	16	13	9
6	18	15	12	9
7	17	15	12	9
8	17	14	11	8

[1] ADT per lane
[2] v/c ratio
Note: Assumed free-flow speed of 35 mph.

downstream section ADT per lane was greater than 15,000 (congested threshold), and when the downstream ADT per lane was greater than the upstream value. An example of this conceptual technique is illustrated in Table 34. It is applied differently in each direction of travel. Note that the "larger" volumes are used.

An analysis of freeway data from Houston using "transposed" ADT per lane values provided the following R^2 values for a linear relationship between ADT per lane and average speed:

- Using actual ADT per lane: $R^2 = 0.50$ and
- Using "transposed" ADT per lane: $R^2 = 0.41$.

This technique did not provide significant advantages in accounting for the effects of freeway bottlenecks. Two problems were encountered in the analysis:

- In some cases, the downstream queue does not extend into the adjacent upstream section.
- In general, there was little information about queuing available for the regression analysis.

"Effective" Volumes. The second conceptual approach weights the upstream section ADT per lane value by the magnitude of the downstream bottleneck (as reflected by the ADT per lane value) and the distance to the bottleneck. An "effective" lane volume was calculated as

$$\begin{aligned} &\textit{Effective ADT per Lane} \\ &\quad = \textit{Bottleneck ADT/Lane}\ [W_1 - W_2 \times d] \end{aligned} \tag{45}$$

where

W_1 = weighting factor for magnitude of bottleneck,
W_2 = weighting factor for distance to bottleneck, and
d = distance to beginning of bottleneck.

A systematic process was used to develop the weighting factors, W_1 and W_2. Several corridors with bottlenecks were chosen, and a systemic analysis optimized the reduction in model error to find the most appropriate weighting factors. Although based on limited data, these weighting factors were optimized at

$W_1 = 1.1$ and
$W_2 = 0.1$.

Greater weighting factors ($W_1 = 1.4$) may be appropriate where lane volumes exceed 30,000 ADT per lane.

As an example of the calculation of "effective" ADT per lane values, see Table 35. This table uses the $W_1 = 1.1$ and $W_2 = 0.1$ value for calculation of effective volumes. From the table, it can be seen that this approach can carry the effects of the bottleneck several miles upstream, *if* the upstream ADT per lane values are considerably lower than the bottleneck ADT per lane (e.g., Bottleneck 1). If the bottleneck ADT per lane is not much larger than the upstream ADT per lane (e.g., Bottleneck 2), the conceptual model will not carry the effects of the bottleneck more than one or two sections upstream.

This conceptual approach produces realistic values, although it was based on several assumptions and limited data. A regression analysis was performed to compare the use of actual and "effective" lane values. The following equation and statistics were obtained for the actual ADT per lane values, taking access frequency into account:

Actual ADT per lane values produced the following equation:

$$\underset{(mph)}{\textit{Average Speed}} = 91.4 - 2.0[\textit{ADT/Lane}(1000s)] - 2.85(\textit{Access Frequency}) \tag{46}$$

n = 59
$R^2 = 0.50$
Root mean square error = 10.2
c.v. = 30%

TABLE 34 Transposed ADT per lane in bottleneck situations

Section Number (from upstream to downstream)		Actual ADT/Lane	"Transposed" ADT/Lane
direction of	1	21,000	26,000
vehicle	2	26,000	26,000
flow	3	26,000	34,000 (> 26,000)
↓	4	34,000	34,000 (> 30,000)
	5	30,000	30,000 (> 28,000)
	6	28,000	28,000 (> 20,000)
	7	20,000	20,000
	8	10,000	10,000
	9	10,000	--

TABLE 35 Effective ADT per lane in bottleneck situations

Section Number (from upstream to downstream)	Section Length (miles)	Actual ADT per Lane	Effective ADT per Lane ($W_1 = 1.1$, $W_2 = 0.1$)
1	1.20	20,900	25,700–Affected by Bottleneck 1
2	0.92	26,125	30,000–Affected by Bottleneck 1
3	0.45	26,125	33,250–Affected by Bottleneck 1
4—Bottleneck 1	0.57	34,800	34,800
5	0.82	30,250	30,250
6	0.92	28,400	28,400
7	0.44	28,400	29,450—Affected by Bottleneck 2
8—Bottleneck 2	0.63	30,800	30,800
9	0.73	30,800	30,800
10	1.15	25,700	25,700
11	0.75	25,700	25,700
12	0.90	25,700	25,700
13	0.98	25,700	25,700
14	0.67	18,000	18,000
15	1.63	18,000	18,000

For the effective ADT per lane values, the following equation and statistics were obtained:

$$\underset{(mph)}{\text{Average Speed}} = 86.4 - 1.5[ADT/Lane(1000s)] - 4.51(Access\ Frequency) \quad (47)$$

$$n = 59$$
$$R^2 = 0.63$$
$$\text{Root mean square error} = 8.74$$
$$\text{c.v.} = 26\%$$

The use of "effective" lane volumes in the regression analysis increased the R^2 value and decreased the model error. Using effective lane volumes, the freeway model error is slightly higher than the arterial street model errors. The R^2 value for the freeway models is substantially higher than the arterial street models.

Implications

The following conclusions were drawn from the freeway analyses:

- Average freeway speeds can be estimated using simple variables like the actual ADT per lane and access frequency (access points per mile). The use of a technique to account for downstream bottlenecks decreased the freeway model error and increased the prediction ability.
- A stratification factor was not used for the freeway data in the regression analysis. The analysis indicated that stratification did not provide major benefits in reducing the model error, perhaps because of the small size of the freeway data set. Data stratification, however, may have significant potential in reducing model variability, as evidenced by the arterial street analyses (greater than 1,000 street segments).
- Equation 47 uses "effective" or weighted ADT per lane values. The statistical analysis indicated that "effective" values improved the prediction ability of the freeway equation. It is recommended that Equation 47 be used in operational analyses and other cases in which quantification of bottleneck effects are important. Equation 47 would be more suitable for planning analyses in which information about bottlenecks is not available or necessary.

The freeway speed prediction model using actual ADT per lane values could be used for planning level analyses to calculate ADT per lane for a given speed and access frequency. Table 36 illustrates a planning application of the surrogate freeway model (Equation 46) for different desired speeds. The target ADTs per lane indicate the volumes that would achieve the desired speeds for specific access frequencies.

For example, a speed of 35 mph is desired on a section of freeway that has two access points per mile. The projected ADT per lane value from a planning model is 30,000 vehicles per lane; however, the "target" ADT/lane from Table 36 is 25,000 vehicles per lane. In this scenario, various land use and transportation management strategies should be adopted to reduce ADT per lane to 25,000 to accomplish the desired speed of 35 mph.

SUMMARY

Congestion can be quantified by directly measuring travel times and by comparing the travel times (or speeds)

TABLE 36 Example of planning application for surrogate freeway model

Desired Speed (mph)	Existing Access Frequency (access points per mile)	Target ADT/Lane (vehicles per lane, 1000s)
25	1.00	32[a]
	1.20	31
	1.50	31
	1.74	31
	2.00	30
	2.25	30
	2.50	30
30	1.00	29
	1.25	29
	1.50	29
	1.75	28
	2.00	28
	2.25	27
	2.50	27
35	1.00	27
	1.20	26
	1.50	26
	1.75	26
	2.00	25
	2.25	25
	2.50	25
40	1.00	24
	1.20	24
	1.50	24
	1.75	23
	2.00	23
	2.25	22
	2.50	22

[a] Target ADT per lane value calculated using Equation 46 for a desired speed.

with acceptable or free-flow traffic conditions. Where travel time estimates are needed over a large area and/or resources are limited, it may be necessary to sample roadway segments in space as well as in time. This chapter has shown how the sample sizes can be obtained for various types of roadways, allowable errors, and levels of confidence.

The chapter also shows how peak-hour travel times can be developed using surrogate travel time estimation techniques. Such approaches have application where direct measurement is impractical, as in assessing future conditions. Application and interpretation of these techniques to routes, corridors, and areas, and their relationship to HCM analyses, are the topics of Chapter 4.

CHAPTER 4

APPLICATION AND INTERPRETATION OF CONGESTION MEASURES

A system of congestion measurement techniques should be based on the needs and questions that will be placed on that system. There is a wide range of potential performance measures for transportation systems, and the congestion measures must complement the other measures and analyses that have been and will be used.

The increased emphasis placed on congestion and mobility measurement by the ISTEA Management Systems and the Metropolitan Planning regulations have altered the needs for estimation procedures and have provided an opportunity to rethink and adjust the measures that have been used in the past. It is important to recognize the usefulness of those procedures. They provide a historic trendline of congestion or mobility levels and, with some minor modifications, may continue to serve the transportation community in the new era of measurement needs.

This chapter presents guidelines for developing a congestion measurement program that quantifies congestion based on travel time-related quantities. The chapter summarizes the measures that can be utilized in the programs and shows how they can be applied at various scales and in various situations. It addresses specific congestion and mobility needs.

DEVELOPING CONGESTION MEASUREMENT PROGRAMS

A more flexible system of performance measures that focuses on the key aspects of both trip making choices and the evaluation of improvement projects and strategies can illustrate the effect of potential solutions, some of which may not even be apparent to the analyst or the professional community at this time. The decision process used by travelers to select trip modes and routes is influenced by travel time, convenience, user cost, dependability, and access to alternative travel choices. The procedures used in the evaluation of improvements consider travel time, capital and operating costs, and various societal and environmental impacts. Travel time is a common thread, both as a direct measure and as an element of other indicators. Savings in travel time underlie many transportation improvements.

A system of performance measurement techniques that use travel time-based measures to estimate the effect of improvements on person travel and freight movement offers a better chance of satisfying the full range of potential needs than the level-of-service measures that became conventional in the last four decades. This does not suggest that past technical procedures are fundamentally flawed or invalid. Rather, it calls for clearly understandable and user-friendly time-based assessments of congestion and mobility. Until recently it was fairly easy to know what type of solution would be implemented because analyses were mode or site specific, there was much less reliance on operational or management solutions, and funding categories dictated very little crossover among highway, transit, and policy solutions. Today's broadened perspective calls for different congestion estimation techniques and broader performance measurement systems and is, in part, simply a reaction to changes in the need for information, rather than an indictment of technical procedures.

Aspects of the Congestion Issue

There are several thoughts on the important attributes of congestion that should be estimated. Many of these were discussed at the Workshop on National Urban Congestion Monitoring (*58*) in May 1990. Four components of roadway congestion that quantify the scope of any problem were identified as a way to begin formulating an overall congestion index. These four components, and other congestion estimation considerations, are discussed here. This discussion builds on the identification of the elements of congestion measurement in the first chapter of this report.

Summarizing Congestion Effects Using Four General Components

While it is difficult to conceive of a single value that will describe all the travelers' concerns about congestion, four components interact in a congested roadway or system. They are duration, extent, intensity, and reliability. They vary among and within urban areas—smaller urban areas, for example, have shorter durations than larger areas.

The components and measurement techniques that can be used to quantify them are discussed in this chapter. They use the definitions of congestion and mobility and the data elements and measures described in this report.

- **Duration**—This is defined as the amount of time congestion affects the travel system. The peak hour has expanded to a peak period in many corridors, and congestion studies have expanded accordingly. Measures that can quantify duration include

–Amount of time during the day that the travel rate indicates congested travel on a system element or the entire system.

–Amount of time during the day that traffic density measurement techniques (detectors, aerial surveillance, etc.) indicate congested travel.

- **Extent**—This is described by estimating the number of people or vehicles affected by congestion and by the geographic distribution of congestion. Measures that quantify person or vehicle congestion extent include

  –Congested travel expressed in person-miles or vehicle-miles that takes place during congested periods.

  –Number or percentage of trips affected by congestion.

  –Number or percentage of person- or vehicle-miles affected by congestion

  Measures of geographic extent include these:

  –Congested roadway in lane-miles or miles.

  –Percent of the system affected by congestion.

- **Intensity**—This is the severity of the congestion that affects travel. It is typically used to differentiate between levels of congestion on transportation systems and to define the total amount of congestion. Measures of intensity include the following:

  –Delay in person-hours or vehicle-hours.

  –Average speed of roadway, corridor, or network.

  –Delay ratio.

  –Delay per capita or per vehicle traveling in the corridor, or per person or vehicle affected by congestion.

  –Relative delay rate.

  –A graph of roadway operating conditions for a time period. Figure 14 illustrates a time and distance graph with the shaded area indicating congestion in individual road segments for discrete time periods (e.g., every 15 min, 30 min, etc.). These are easy to develop when travel time data are available for each time period.

  –The product of lane-miles of congested roadway and duration of congestion. This is essentially calculating the area (roadway space multiplied by time) of the contour map. This can be expressed as minute-miles (as used in Chicago) (*11*) or lane-mile hours (*56*).

  –Accessibility. Severity of congestion can be highlighted by separately quantifying and contrasting peak and off-peak accessibilities.

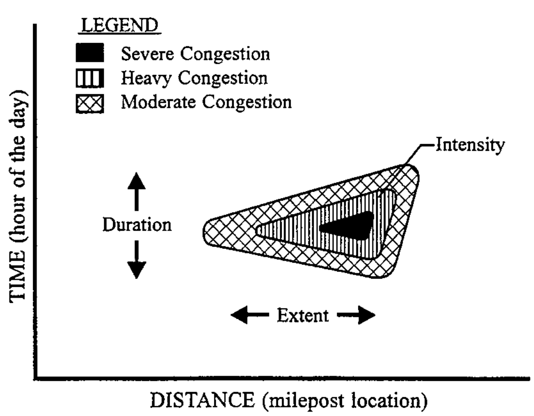


Figure 14. Intensity of congestion—relationship between duration and distance.

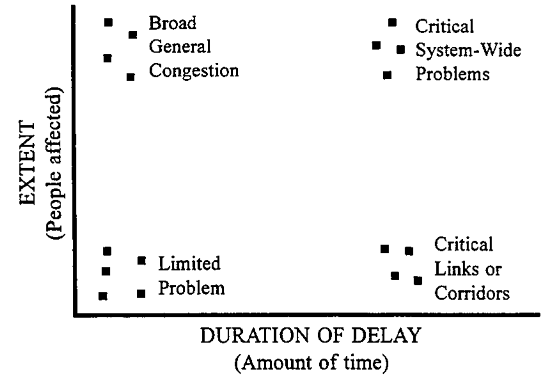


Figure 15. Intensity of congestion—relationship between extent and duration of delay.

The relationship among duration, extent, and intensity is illustrated in Figures 14 and 15. The variation in extent and duration of congestion indicates different problems requiring different solutions. The product of the two quantities indicates the intensity, or magnitude, of the congestion problem.

- **Reliability**—This key component of congestion estimation is described as the variation on the other three elements. Recurrent (daily congestion caused by excessive traffic volume) delay varies due to the amount of traffic at certain times, or on certain days or seasons while capacity remains fixed. This quantity is relatively stable and somewhat predictable. Nonrecurrent (due to accidents, vehicle breakdown, weather, etc.) delay causes further variation in the amount of congestion and is much less easily predicted. Reliability is the impact of nonrecurrent congestion on the transportation system, and can be measured with the following quantities:

  –The variations in travel time can be expressed as an average travel time or rate plus or minus a standard deviation component. This is particularly easy with the automated travel time data collection processes being installed in some Intelligent Transportation System projects.

–Travel time contour maps displaying the distance covered on the average day in x minutes, and other lines delineating the distance covered in some percentage of the days (e.g., 25 and 75 percent of the daily peak periods).
–Difference in delay on incident days and nonincident days. This quantity adapts the intensity measure to an illustration of the effect of incidents.

The types of measures that should be used for each congestion component in assessing congestion on individual roadways, in a corridor, or for an areawide network are summarized in Table 37. Details of applying these measures for different locational analyses or scales are discussed in another major section of this chapter.

Data Collection Focus

It is recommended that travel time and speed studies should be used to directly collect congestion data whenever feasible. These data can be used to quantify congestion, identify bottlenecks in traffic systems, evaluate computerized coordinated traffic signal systems and other operational improvements designed to move traffic more efficiently, provide data for air quality analyses, and improve analyses and feasibility studies for a range of multimodal and intermodal improvements. Traffic counting programs can be more effectively targeted when system bottlenecks are identified. For corridor, subarea, or regional analyses, travel speeds can be sampled on a few routes in the same way that traffic counts are sampled. Travel time data also can be collected in conjunction with traffic counts.

Where direct measurement of travel time quantities is not feasible, surrogate measures should be used to estimate the travel rate. The procedures suggested in this report can then be used to estimate congestion levels. Alternatively, vehicle-based analysis procedures (e.g., HCM) can be extended so that the output quantities can be transformed into person volume, and travel speed or travel rate values.

Role of Highway Capacity Manual Procedures

The use of HCM-based procedures to estimate congestion provides the starting point for many agencies in congestion measurement. While travel speed is not the measure of effectiveness used for many analyses in the HCM (*8*), speed or travel rate can be derived, or is derived, as part of many analysis procedures. Many groups and agencies will

TABLE 37 Overview of methods to measure congestion aspects

Congestion Aspect	System Type		
	Single Roadway	Corridor	Areawide Network
Duration (e.g., amount of time system is congested)	Hours facility operates below acceptable speed	Hours facility operates below acceptable speed	Set of travel time contour maps; "bandwidth" maps showing amount of congested time for system sections
Extent (e.g., number of people affected or geographic distribution)	% or amount of congested VMT or PMT; % or lane-miles of congested road	% of VMT or PMT in congestion; % or lane-miles of congested road	% of trips in congestion; person-miles or person-hours of congestion; % or lane-miles of congested road
Intensity (e.g., level or total amount of congestion)	Travel rate; delay rate; relative delay rate; minute-miles; lane-mile hours	Average speed or travel rate; delay per PMT; delay ratio	Accessibility; total delay in person-hours; delay per person; delay per PMT
Reliability (e.g., variation in the amount of congestion)	Average travel rate or speed ± standard deviation; delay ± standard deviation	Average travel rate or speed ± standard deviation; delay ± standard deviation	Travel time contour maps with variation lines; average travel/time ± standard deviation; delay ± standard deviation

Note: VMT—vehicle-miles of travel
PMT—person-miles of travel

continue using HCM procedures to estimate levels of service, which in some cases imply congestion levels. It should be noted, however, that the design and operational analyses in HCM have different objectives and end products than a congestion estimation procedure. They are better suited to identifying location-specific problems than to assessing route, corridor, or areawide congestion levels. Estimating density or stopped delay to estimate a level-of-service, for example, provides information to operations and design personnel, but must be further manipulated to quantify congestion problems. Just as congestion estimates cannot be used to re-time signals, level-of-service measures cannot support many uses and needs of congestion measures, particularly on a system basis, nor do they assess the intensity and duration of congestion.

Congestion estimates on arterial streets using travel time study data can directly evaluate the effect of coordinated signals and are able to determine the difference between delay due to signal operation (using travel rates during the midday off-peak or the nighttime periods) and delay due to high traffic volume. The HCM procedure for arterial streets relies on estimates of capacity, quality of signal progression, and the relationship of approach delay to stopped delay, as well as using proxy measures for factors such as parking, driveways, and minor street traffic. They focus on surrogate rather than direct estimates of congestion.

Use of HCM in oversaturated intersection conditions, where the volume-to-capacity ratio is above 1.0, is treated with a cautionary note in the HCM. Use of delay estimates for conditions above a volume-to-capacity ratio of 1.2 is not recommended because of the queues that develop and affect adjacent intersections. The HCM cautions that "oversaturation is an undesirable condition that should be ameliorated if possible" (*8*). Ongoing research for the year 2000 HCM is, however, attempting to deal with oversaturated (level-of-service F and beyond) conditions. In situations such as this, direct measurement or sampling of travel rate or the development of new procedures to estimate congestion levels is extremely useful, since they can pinpoint the location, intensity, and duration of congestion.

Use of Surrogate Estimation Procedures

Any surrogate estimate should be developed and used recognizing the potential error introduced when such estimates are derived. Surrogate travel time estimation procedures are most applicable for policy, programming, or planning purposes. The surrogate techniques are especially useful for estimating future conditions, but also have application for existing conditions when direct measurement or travel time sampling is not possible or practical.

Surrogate estimation procedures will be required to compare current conditions to future conditions. If travel speeds are determined for existing roadways using the floating car or some other direct method, a separate estimate of the surrogate speed must be made for existing conditions. The future speed will be calculated using Equation 48, which combines surrogate estimates for existing and future conditions with existing travel speeds. This process reduces the error that would be induced by comparing actual speeds to estimated speeds.

$$\begin{matrix}\textit{Future}\\ \textit{Estimate}\end{matrix} = \textit{Existing} \times \frac{\textit{Future Surrogate}}{\textit{Existing Surrogate}} \tag{48}$$

Arterial street speeds can be estimated using Figures 10 through 13; Tables 32 and 33; or Equations 40, 41, and 42. The required input variables include traffic volume level (v/c ratio or ADT per lane), signal density, and arterial class (as defined in the 1994 *Highway Capacity Manual*). The speeds for Class I arterials are calculated using a different graph from Class II and III arterials.

Freeway speeds can be estimated using Equations 46 and 47. The required input variables include traffic volume level (ADT per lane) and access frequency (access points per mile). Equation 47 uses "effective" ADT per lane values that are weighted by the magnitude of and distance from a freeway bottleneck. Equation 47 is more appropriate for operational analyses where the quantification of bottleneck effects is necessary. Equation 46 uses actual ADT per lane values and is suitable for planning and programming purposes where bottleneck information is not available or necessary.

Summary

The research provides a framework for measuring highway traffic congestion. However, the procedures can be adapted to quantify the congestion associated with the movement of people and goods. This can be achieved by taking vehicle occupancies and types into account, and by looking at public transport movements in both mixed-flow traffic and segregated rights-of-way. Such an analysis is consistent with the goals of a transportation system—to move people and goods safely, quickly, and reliably.

Estimates of both mobility and congestion can be obtained by analyses and measurement of speed and travel rates. Within this context, various transportation groups should reexamine their current practices of congestion estimation in light of the needs for information and their responsiveness to potential improvement projects or programs. The broader contemporary perspective suggests that traditional highway capacity analysis procedures be complemented by direct travel time measurements and assessments, especially in the future.

Thus, an evolutionary plan of congestion assessment should emerge. Limited travel time studies in severely congested locations or corridors may improve congestion estimates initially, with more extensive use of direct measurement to follow as funds are available, advanced technology systems are installed, or congestion levels rise toward unacceptable levels. It is important to retain some historical database whenever possible to allow trend analyses to be developed. The limited initial travel time studies may provide the very useful function of calibrating local congestion estimation equations from national averages.

Direct collection of travel time and speed data is encouraged whenever possible to provide information for local studies, to provide a basis for congestion trend monitoring, and to calibrate national averages to local freeway and street operation. Surrogate travel time estimation techniques may, however, be necessary where resource constraints exist or where it is desired to assess future conditions. Figure 16 illustrates the relationship between direct data collection and the use of surrogate measures.

APPLICATION OF TECHNIQUES AT DIFFERENT LEVELS OF ANALYSIS

Developing a system of congestion measures should be initiated only after an examination of the uses, users, and audiences to be served, and after full consideration of program goals and objectives and the nature of likely solutions. This chapter illustrates a system of travel time-based measures to estimate congestion levels. These procedures are useful for roadway systems, other person and freight movement modes, and transportation improvement strategies and programs. Although a number of analyses may not benefit from such a broader focus, consideration of the context in which the measures are to be used will allow the user to identify the appropriate set of congestion measures.

Congestion measures are applied in different geographic settings, in different time frames, at differing levels of detail and at different scales, and under existing, changed and future conditions. They must accurately describe present conditions and be capable of being forecast for the future. There is a need for measures that can be applied across all passenger modes of urban travel individually and simultaneously. The majority of congestion measure applications remain highway oriented, but with increased emphasis on the movement of people. Multimodal uses are increasing in response to CAAA and ISTEA requirements, HOV and transit components of IVHS programs, and expanding interest in pairing transportation management with growth management.

The following sections describe techniques for measuring congestion on various sections of a transportation network. Examples are used to illustrate the application of the basic measures to typical situations of system evaluation or analysis of alternative improvements. Single mode and multimodal systems are integrated in the examples.

Applying Analysis Methods

The research clearly indicates the need to separate the issues of data collection from the measures that are used in technical analyses and presentations. The measures that are needed to evaluate the transportation system or the effect of improvements are the most important consideration. Data collection or measurement estimates can be developed in a variety of ways; these are important elements of a congestion monitoring program, but they should not be the key consideration in deciding which measures are used.

While direct measurement of travel time and speed is desirable for evaluation of existing congestion, it is not always practical. Moreover, when future conditions are ana-

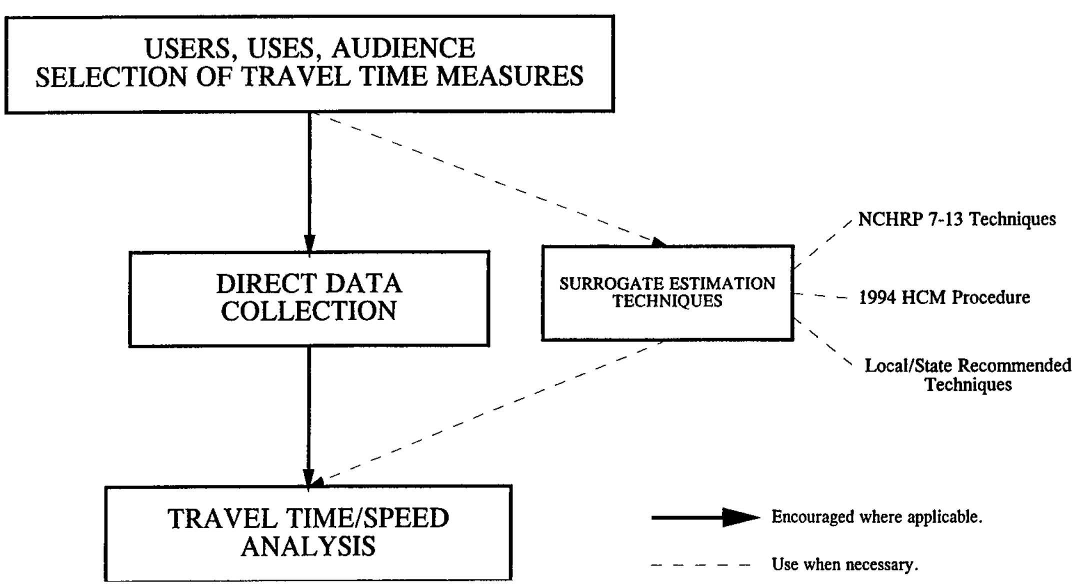


Figure 16. Application of surrogate techniques in quantifying congestion.

lyzed, the travel time data that would be helpful in assessing potential effects of operational improvements or judging cost effectiveness of additional roadway lanes are obviously not available to be collected. Travel time and speed estimating procedures are needed for situations like this and are thus an important part of the congestion measurement process. Overall, there are several ways to accomplish measurement and estimation of congestion information.

The travel time and speed estimating procedures that are needed include relatively simple procedures that use easily obtained data, procedures that can be used by agencies responsible for system operations, and procedures that work well with travel demand models.

Table 38 shows how the three basic categories of analysis relate to the four most common types of analysis. It serves as a general guide for practitioners for generating congestion information and for identifying the appropriate data collection and analysis strategies.

Function. For most types of general policy, programming, or planning purposes, the surrogate estimation procedures will provide useful results with a minimum of data collection. More specific design and operation concerns will require more precision, and direct measures of travel time or travel speed will usually be required.

Analysis Period. Most techniques can produce useful information for existing conditions, but future conditions will require some surrogate procedures (e.g., travel time or HCM). Surrogates will also be required for existing conditions where future scenarios will be analyzed. This approach will provide uniformity of estimation, avoiding inconsistencies associated with differences in roadway system operations.

Analysis Scope and Scale. HCM analysis procedures will be used for most intersection analyses and possibly for short roadway segments; direct travel time measures will be more useful for analysis areas greater than short roadway segments. If large corridors, subareas, or regions are to be analyzed, some sampling process will be useful to limit data collection requirements.

Free-Flow Travel Conditions

If estimated free-flow travel rates or speeds are used in the calculation of delay, the speed data collected from field studies may include values with faster speeds or lower rates. Computerized analysis procedures should be modified so that a "negative delay" value is not included in the calculations. If the direct collected speeds are frequently higher than the designated free-flow speeds, the free-flow values should be changed.

Common Data for All Examples

The basic formulas for congestion measurement are listed in Table 39. Each measure is described in more detail elsewhere, but this summary is provided for easy reference in the

TABLE 38 Applications of congestion analysis methods

Analysis Category	Type of Analysis Method			
	Highway Capacity Manual	Direct Travel Time Measurement	Sampling Travel Time on Segments	Surrogate Travel Time Procedures
Function				
Policy Analysis				#
Project Prioritization				#
Planning or Alternative Analysis		✓	#	#
Design	✓	#	#	
Operation	#	✓		
Analysis Period				
Existing Conditions	#	#	#	✓[1]
Future Conditions				
Short range	#	#	#	✓[1]
Long range	✓			#
Analysis Scope and Scale				
Intersections	#	✓		
Single Roadway	✓	#	✓	
Corridor		#	#	✓
Sub-area			#	#
Areawide			#	#

Application in most analyses.
✓ Limited application.
[1] Particularly when needed as base condition for analysis of future conditions.

TABLE 39 Quick reference guide to measure of congestion

TRAVEL RATE	$\underset{\text{(minutes per mile)}}{\text{Travel Rate}} = \dfrac{\text{Travel Time (minutes)}}{\text{Segment Length (miles)}} = \dfrac{60}{\text{Average Speed (mph)}}$
DELAY RATE	$\underset{\text{(minutes per mile)}}{\text{Delay Rate}} = \underset{\text{(minutes per mile)}}{\text{Actual Travel Rate}} - \underset{\text{(minutes per mile)}}{\text{Acceptable Travel Rate}}$
TOTAL DELAY	$\underset{\text{(vehicle-minutes)}}{\text{Total Segment Delay}} = \left[\underset{\text{(minutes)}}{\text{Actual Travel Time}} - \underset{\text{(minutes)}}{\text{Acceptable Travel Time}}\right] \times \underset{\text{(vehicles)}}{\text{Vehicle Volume}}$
PERSON-SPEED	$\underset{\text{(person-mph)}}{\text{Person-Speed}} = \underset{\text{(persons)}}{\text{Passenger Volume}} \times \underset{\text{(mph)}}{\text{Average Travel Speed}}$
RELATIVE DELAY RATE	$\text{Relative Delay Rate} = \dfrac{\text{Delay Rate}}{\text{Acceptable Travel Rate}}$
DELAY RATIO	$\text{Delay Ratio} = \dfrac{\text{Delay Rate}}{\text{Actual Travel Rate}}$
CONGESTED TRAVEL	$\underset{\text{(vehicle-miles)}}{\text{Congested Travel}} = \text{Sum of all}\left(\underset{\text{(miles)}}{\text{Congested Segment Length}} \times \underset{\text{(vehicle)}}{\text{Traffic Volume}}\right)$
CONGESTED ROADWAY	$\underset{\text{(miles)}}{\text{Congested Roadway}} = \text{Sum of all Congested Segment Lengths (miles)}$
ACCESSIBILITY	$\underset{\text{(opportunities)}}{\text{Accessibility}} = \sum \text{Objective fulfillment opportunities (e.g., jobs), where Travel time} \le \text{Acceptable travel time}$

examples. Table 40 describes the calculations and format used in the examples. The lines of data are labeled, and the calculations refer to the labels so that the information is easier to understand and code into spreadsheet or database formats.

Table 41 illustrates the acceptable travel rates used in the examples. In a typical application these would be developed with input from citizens, businesses, decision makers, and transportation professionals. They represent the crucial link between (1) the vision that the community has for its transportation system, land uses, and its "quality of life" issues and (2) the improvement strategies, programs, and projects that government agencies and private sector interests will implement. The values are desirably the result of a process that is integrated with the development of the long-range plan, but they must be reasonable and realistic, since overstatement or understatement could distort congestion assessment. The level of information needed to carry out this type of process at an optimum level is not currently distributed in most urban areas. The values can, however, be interpreted from existing input processes. **The values in Table 41 are for illustration purposes only.**

The examples in this section are for several levels of analysis from isolated locations to regional analyses, but they are based on individual facility evaluations. These include segments of freeways and streets, with general purpose traffic, as well as buses, rail transit, and carpools. The examples also show several alternative improvements that might be proposed to address congestion and mobility problems including better operational efficiency, increases in transit and rideshare use, and improvements in operations through improved traffic signals and incident response.

Urban areas should approach the use of acceptable travel rates with a systemwide strategy. They should recognize that

TABLE 40 Formula descriptions for congestion measurement examples

Label	Measure	Units	Formula Description
a	Length	Miles	input value
b	Vehicle Volume	Vehicles	input value
c	Person Volume	Persons	b x f
d	Vehicle-Miles	Vehicle-Miles	a x b
e	Person-Miles	Person-Miles	a x c
f	Avg. Vehicle Occup	Persons/Veh	collected value
g	Acceptable Travel Rate	Minutes/Mile	input value
h	Acceptable Travel Speed	Miles/Hour	60 ÷ g
i	Free-Flow Travel Rate	Minutes/Mile	collected value
j	Actual Travel Rate	Minutes/Mile	collected value
k	Actual Travel Speed	Miles/Hour	60 ÷ j
l	Actual Travel Time	Person-Hours	(e x j) ÷ 60
	Delay Rate		
m	vs. Acceptable	Minutes/Mile	j - g
n	vs. Free-Flow	Minutes/Mile	j - i
o	Standard Deviation of Actual Travel Rate	Minutes/Mile	collected value
	Delay (vs. Acceptable)		
p	Vehicle Travel	Vehicle-Hours	(d x m) ÷ 60
q	Person Travel	Person-Hours	(e x m) ÷ 60
	Delay Range		
r	Min. Std. Deviation	Person-Hours	e x (m - o) ÷ 60
s	Max. Std. Deviation	Person-Hours	e x (m + o) ÷ 60
	Delay Per:		
t	Person Mile	Person-Minutes	(q x 60) ÷ e
u	Mile of Road	Person-Hours	q ÷ a
	Congested Travel Summary		
v	Person-Miles	Person-Miles	Sum of congested person-miles (line e if line m is greater than zero).
w	Person-Hours	Person-Hours	Sum of congested person hours (line l if line m is greater than zero).
x	Miles of Congested Roadway	Miles	Sum of congested miles (line a if line m is greater than zero)
y	Relative Delay Rate	No units	m ÷ g
z	Delay Ratio	No units	m ÷ j
aa	Corridor Mobility Index	No units	$(c \times k) \div \left(\frac{25{,}000 \times \#\ \text{lanes - street}}{125{,}000 \times \#\ \text{lanes fwy}}\right)$

Note: Lower values indicate better conditions for all measures except Corridor Mobility Index (line aa).

Average values are calculated using person-miles as the weighting value. Example:

$$\textit{Actual Travel Rate} = \frac{\sum\left(\textit{Section and Mode Travel Rate Value} \times \textit{Section and Mode Person-Miles}\right)}{\textit{Total Person-Miles}}$$

the acceptable targets may not be achievable for every roadway situation. Other travel mode improvements, strategies or policies may be needed. For example, the freeway travel rates in Table 41 are not low enough to justify an HOV lane under normal circumstances. It is likely, however, that the freeway speeds will be lower than those in Table 41 in most large urban areas. An HOV lane can contribute to bringing the average travel rate for the corridor, when weighted by person volume, closer to the target value.

The examples are focused on the appropriate level of detail necessary to identify the effect of a proposed treatment. For most alternatives this is at the corridor level or more detailed;

TABLE 41 **Acceptable travel rate values used in examples**

PEAK PERIOD						
Area Type	Acceptable Travel Rates (minutes per mile)					
	Freeway Mainlane	Freeway HOV Lane	Major Street	Bus on Street	Rail in Street	Bike
Central Business District	1.7	1.0	5.0	7.0	6.0	6.0
Central City/ Major Activity Center	1.5	1.0	3.0	5.0	4.5	5.5
Suburban	1.33	1.0	2.4	4.0	4.0	5.0
Fringe	1.2	0.9	2.0	3.5	3.0	4.0
OFF-PEAK PERIOD						
Area Type	Acceptable Travel Rates (minutes per mile)					
	Freeway Mainlane	Freeway HOV Lane	Major Street	Bus on Street	Rail in Street	Bike
Central Business District	1.5	0.9	3.0	5.0	4.5	5.0
Central City/ Major Activity Center	1.0	0.9	2.5	4.0	4.0	4.5
Suburban	1.0	0.9	2.0	3.5	3.5	4.0
Fringe	1.0	0.9	1.5	3.0	2.5	4.0

Assumes that these rates reflect a consensus of input from technical and non-technical groups. For educational purposes, there should be an information packet for citizens that includes data on the relationship between economic development, environmental impact, land use and transportation system choices.

this is the area where the effect of the improvement can be identified and the reasonableness of the measurement techniques can be checked. The magnitude of the numbers for a wider area may mask the impact of a single improvement, especially for relatively small changes. The corridor level of analysis is also where most projects are evaluated, prioritized, and funded.

Focusing on individual facilities or modes, however, is not consistent with the manner in which most travelers make their choices. Door-to-door travel time is closer to the primary measure used by travelers and is best expressed in accessibility measures. Unfortunately, it is difficult to translate an accessibility measure like "population within 30 minutes' travel time of a major activity center" into a procedure to evaluate signal improvements on an arterial street. The transportation and land use planning model required to calculate the accessibility may not be sensitive enough to identify the improvement in travel conditions.

The method to connect accessibility measures with the many smaller scale analyses is the acceptable travel condition values. The acceptable travel time and travel rate conditions identify when the citizens believe improvements should be made. The conditions that citizens find unacceptable will be a mix of economic development, transportation, and quality of life considerations. The discussion about what constitutes unacceptable conditions could be conducted in conjunction with the long-range planning process and the future visions of the area.

The examples depict peak-hour conditions, but the same procedures can be used for peak-period and daily analyses. The weighting process used in the examples to calculate averages and totals for different modes and sections of roadway—using person-volume—is the same one used to calculate peak-period and daily measures. The peak-hour focus used here allows the users to see the calculation procedures and usage of the statistics. The peak period is the minimum appropriate analysis period for situations in which congestion exists, or is forecast, beyond the peak hour. Post-project evaluations may show no improvement in peak-hour performance, but there may be reductions in the length of the peak period that are affected by congestion.

Individual Locations

Analyses of individual locations (e.g., intersections) should be performed according to the 1994 *Highway Capacity Manual* (*8*) procedures or other commonly accepted intersection or site analysis procedures. Stopped delay intersection studies can be used to directly collect delay information. Observations of traffic backups—their extent and duration—are very useful.

It is difficult to apply travel time and speed study types to the analysis of intersections. Floating car runs or license plate matching studies are not very meaningful for short distances in which one signal controls the variability of travel speeds. As traffic signals are connected into systems, however, it will become more difficult to analyze any intersection in isolation and longer sections of roadway will become the basic unit for more analyses.

Suggested Measures. Traditional measures of service quality at signalized intersections include stopped delay per vehicle and the number of stops. It is suggested that the measures of **person delay or vehicle delay** and/or **delay per vehicle or per person** be considered for intersection and approach roadway congestion studies. These measures are consistent with current intersection analysis measures and provide the ability to calculate quantities that reflect the importance of person movement. These quantities can be developed from direct data collection efforts or from the Highway Capacity Manual procedures. **Accessibility** can be used productively to examine the effect of area transportation conditions on travel associated with localized site development but has little applicability to evaluating traffic operations at individual locations.

Short Roadway Sections

The analysis of short roadway sections, on the magnitude of one to three or four miles, differs somewhat from the analysis of longer roadway sections. Short roadway sections may match existing divisions of roadway inventory data or could include several relatively homogenous roadway links between intersections and interchanges. These individual roadway links within a short section should have similar cross sections, traffic volumes, and operating conditions. Individual links that have different cross sections or operating conditions should not be combined together to form a short roadway section. Instead, roadway links with different characteristics should be considered separately or with other adjacent links that have similar characteristics.

The use of travel time and travel rate data is well suited to the analysis of roadway sections. Travel times between intersections or interchanges can be added to match the appropriate section length. Because the cross section and traffic volumes are similar for each link, a single average or representative data value can be used to represent all links within a section. Congestion on short sections can be identified by comparing actual travel rates to acceptable travel rates.

Suggested Measures. Appropriate measures for short roadway sections include the **average travel rate, delay rate, total person or vehicle delay, delay ratio,** and the **relative delay rate.** These measures would provide useful information at this level of analysis. The average travel rate and delay rate can be used on absolute terms, or can be used to compare similar classes of facilities. The relative delay rate, the delay ratio, and total delay can be used to compare different classes of facilities.

Highway Capacity Manual procedures may be used to develop estimates for these quantities. In severely congested corridors or for before/after studies of coordinated or adaptive signal systems (systems that can change timing plans several times during the peak in response to demand), however, direct data collection studies will be more appropriate and useful in estimating congestion levels.

Example. Tables 42 and 43 illustrate several key congestion statistics for a freeway and a major street. These statistics are similar to those that would be used if a congestion evaluation were performed on an individual facility or as one part of an areawide analysis. License plate matching, floating car travel time runs, or automated vehicle monitoring could be used to develop the travel time and speed information. Roadway inventory files could be used to identify logical section limits as well as other useful information, such as number of lanes.

Town Avenue. Two sections of four-lane Town Avenue are displayed in Table 42. The auto and bus modes are separated because the travel speed and vehicle occupancy rates are significantly different. Improvements to the sections may also change the travel characteristics of the modes differently, so the data were collected separately. The total or average column presents information on both sections together.

The length, volume, and total travel time information (lines a through e and l) are used in calculating cumulative statistics and in weighting for average statistics. The acceptable travel rates are less than the free-flow rates, indicating that some level of congestion is considered acceptable for this portion of the system. The actual travel rates are significantly less than the acceptable rates, indicating a need for improvements to attain the acceptable travel rates.

The most useful statistics for evaluations are found in lines m through s. The delay rate is calculated relative to both acceptable speeds and free-flow conditions. The acceptable travel rate is the value that would be used to compare alternative improvement projects, while the free-flow comparison is useful in quantifying areawide congestion levels. The delay values are the cumulative statistics that would be used in estimating the benefit/cost relationship for new projects or improvement strategies.

The delay range indicates the impact of travel condition variability on the total delay amount. The standard deviation statistic used in this calculation (line o) can be compiled for individual roadways or can be estimated from studies of the effect that roadway design, functional class, and adjacent development have on travel variability.

TABLE 42 Existing operation on Town Avenue

Location: Suburban
Travel Period: Morning Peak Hour
Travel Direction: Northbound (Peak Direction)
Alternative: Existing Operation

Label	Measure	Units	System Element				Total or Average
			Elm to Maple		Maple to Oak		
			Auto	Bus	Auto	Bus	
a	Length	Miles	2.8	2.8	3.5	3.5	6.3
b	Vehicle Volume	Vehicles	1,000	8	1,200	10	
c	Person Volume	Persons	1,200	250	1,450	300	
d	Vehicle-Miles	Vehicle-Miles	2,800	22	4,200	35	7,057
e	Person-Miles	Person-Miles	3,360	700	5,075	1,050	10,185
f	Avg. Vehicle Occup	Persons/Veh	1.20	31.25	1.21	30.00	1.44
g	Acceptable Travel Rate	Minutes/Mile	2.40	4.00	2.40	4.00	2.67
h	Acceptable Travel Speed	Miles/Hour	25	15	25	15	
i	Free-Flow Travel Rate	Minutes/Mile	2.25	3.50	2.25	3.50	
j	Actual Travel Rate	Minutes/Mile	5.00	7.50	6.00	8.57	6.04
k	Actual Travel Speed	Miles/Hour	12	8	10	7	
l	Actual Travel Time	Person-Hours	280	88	508	150	1,025
	Delay Rate						
m	vs. Acceptable	Minutes/Mile	2.60	3.50	3.60	4.57	3.36
n	vs. Free-Flow	Minutes/Mile	2.75	4.00	3.75	5.07	3.57
o	Standard Deviation of Actual Travel Rate	Minutes/Mile	0.5	0.7	0.5	0.7	0.5
	Delay (vs. Acceptable)						
p	Vehicle Travel	Vehicle-Hours	121.3	1.3	252.0	2.7	377
q	Person Travel	Person-Hours	145.6	40.8	304.5	80.0	571
	Delay Range						
r	Min. Std. Deviation	Person-Hours	117.6	32.7	262.2	67.8	480
s	Max. Std. Deviation	Person-Hours	173.6	49.0	346.8	92.3	662

Note: See Table 40 for calculation procedures and Table 41 for acceptable travel rate values.

Westside Freeway. The statistics for this section of six-lane Westside Freeway are the same type as those presented for Town Avenue. This section of Westside Freeway is also congested relative to both free-flow and acceptable values. The bus volume on the freeway is double that on Town Avenue, but the autos in the freeway mainlanes carry many more persons than the buses such that the cumulative statistics are governed by the auto travel conditions. Since the buses are not stopping on the freeway, as they do on the street, their performance statistics are very similar to the autos with respect to speed and speed reliability.

Long Roadway Sections or Routes

The analysis of long roadway sections or routes, generally greater than 4 to 5 mi, must take into consideration the different operating characteristics of the roadway along the entire length. Routes will contain two or more short roadway sections with different cross sections and operating characteristics. Consequently, congestion studies must recognize and account for the different operating conditions along the route. Average or representative travel time values should be developed for each short roadway section within a route, and various cumulative statistics can be calculated for the entire route.

Suggested Measures. Average statistics, like the average travel rate and the average delay rate, are weighted by the length of each segment and may be less meaningful for long routes or routes with widely varying conditions. Cumulative statistics, like **total delay, congested travel,** and **congested roadway** may provide more useful information for these longer routes. Again, vehicle occupancies should be used to obtain person-delay.

Town Avenue Example. Longer route section summaries can either identify each mode individually (as in Table 42) or present the statistics as a combination of all

TABLE 43 Existing operation on Westside Freeway

Location: Suburban
Travel Period: Morning Peak Hour
Travel Direction: Northbound (Peak Direction)
Alternative: Existing Operation

Label	Measure	Units	System Element				Total or Average
			1st to 8th		8th to 15th		
			Auto	Bus	Auto	Bus	
a	Length	Miles	4.4	4.4	4.0	4.0	8.4
b	Vehicle Volume	Vehicles	5,800	20	5,500	20	
c	Person Volume	Persons	6,960	650	6,600	650	
d	Vehicle-Miles	Vehicle-Miles	25,520	88	22,000	80	47,688
e	Person-Miles	Person-Miles	30,624	2,860	26,400	2,600	62,484
f	Avg. Vehicle Occup	Persons/Veh	1.20	32.50	1.20	32.50	1.31
g	Acceptable Travel Rate	Minutes/Mile	1.33	1.00	1.33	1.00	1.30
h	Acceptable Travel Speed	Miles/Hour	45	60	45	60	
i	Free-Flow Travel Rate	Minutes/Mile	0.90	0.90	0.90	0.90	
j	Actual Travel Rate	Minutes/Mile	2.40	2.40	3.00	3.00	2.68
k	Actual Travel Speed	Miles/Hour	25	25	20	20	
l	Actual Travel Time	Person-Hours	1,225	114	1,320	130	2,789
	Delay Rate						
m	vs. Acceptable	Minutes/Mile	1.07	1.40	1.67	2.00	1.37
n	vs. Free-Flow	Minutes/Mile	1.50	1.50	2.10	2.10	1.78
o	Standard Deviation of Actual Travel Rate	Minutes/Mile	0.5	0.5	0.5	0.5	0.5
	Delay (vs. Acceptable)						
p	Vehicle Travel	Vehicle-Hours	453.7	2.1	611.1	2.7	1,070
q	Person Travel	Person-Hours	544.4	66.7	733.3	86.7	1,431
	Delay Range						
r	Min. Std. Deviation	Person-Hours	289.2	42.9	513.3	65.0	910
s	Max. Std. Deviation	Person-Hours	799.6	90.6	953.3	108.3	1,952

Note: See Table 40 for calculation procedures and Table 41 for acceptable travel rate values.

modes on the route. Table 44 shows the simpler nature of the combined mode format for sections with several road segments. The Elm to Oak segment statistics are drawn from Table 42 and combined with the Oak to Pine segment, which is less congested. The actual travel rate is faster than that acceptable for Oak to Pine and equal to the free-flow rate. This is presented as no delay in line m or line n. The standard deviation is also slightly less in the less-congested section, possibly due to the lower volume, which allows for minor incidents to be handled without much impact on traffic flow.

Travel conditions in longer sections are more easily described by the cumulative statistics in lines t through x. Using person-miles of travel to weight the individual section values results in a measure of the average condition seen by the travelers in the Elm to Pine section of Town Avenue. An average of 2.8 minutes of delay is incurred by the travelers on Town Avenue and an average of 68 person-hours of delay is incurred daily on each mile of this section of Town Avenue. These averages obviously hide some of the problems between Elm and Oak, but these are identified in the person-miles, person-hours, and miles of congested roadway statistics. These are developed by summing the statistics (for lines e, l, and a) in every section of road that is congested (Elm to Oak).

Corridors

The analysis of congestion along corridors would be similar to a route analysis, but could include parallel freeway and arterial street routes that serve dense travel corridors. At this level of analysis, surrogate measurement techniques could be combined with direct data collection to obtain the necessary information. A calibration process would be required to correlate the direct and surrogate statistics so that variations in estimated travel speed are due to traffic conditions and not due to differences in the measurement technique.

The number of data collection sites could be governed by a statistical sample of the routes or could be performed for all major movements in the corridor. The calculation of average travel and delay rates for the corridor as a whole would be based on individual segment data. Statistics for each segment

TABLE 44 Congestion estimate for long section of Town Avenue

Location: Suburban
Travel Period: Morning Peak Hour
Travel Direction: Northbound (Peak Direction)
Alternative: Existing Operation

Length	Measure	Units	System Element			Total or Average
			Elm to Maple	Maple to Oak	Oak to Pine	
a	Length	Miles	2.8	3.5	2.1	8.4
b	Vehicle Volume	Vehicles	1,008	1,210	700	
c	Person Volume	Persons	1,450	1,750	1,000	
d	Vehicle-Miles	Vehicle-Miles	2,822	4,235	1,470	8,527
e	Person-Miles	Person-Miles	4,060	6,125	2,100	12,285
f	Avg. Vehicle Occup	Persons/Veh	1.44	1.45	1.43	1.44
g	Acceptable Travel Rate	Minutes/Mile	2.68	2.67	2.67	
h	Acceptable Travel Speed	Miles/Hour	23.3	23.3	23.3	
i	Free-Flow Travel Rate	Minutes/Mile	2.5	2.5	2.5	
j	Actual Travel Rate	Minutes/Mile	5.4	6.4	2.5	
k	Actual Travel Speed	Miles/Hour	11.3	9.5	24.0	
l	Actual Travel Time	Person-Hours	368	658	88	1,113
	Delay Rate					
m	vs. Acceptable	Minutes/Mile	2.8	3.8	0	
n	vs. Free-Flow	Minutes/Mile	3.0	4.0	0.0	
o	Standard Deviation of Actual Travel Rate	Minutes/Mile	0.5	0.5	0.4	
	Delay (vs. Acceptable)					
p	Vehicle Travel	Vehicle-Hours	123	255	0	377
q	Person Travel	Person-Hours	186	385	0	571
	Delay Range					
r	Min. Std. Deviation	Person-Hours	150	330	0	480
s	Max. Std. Deviation	Person-Hours	223	439	20	682
	Delay Per:					
t	Person Mile	Person-Minutes	2.8	3.8	0	2.8
u	Mile of Road	Person-Hours	67	110	0	68
	Congested Travel					
v	Person-Miles					12,285
w	Person-Hours					1,113
x	Miles of Congested Roadway					6.3

Note: See Table 40 for calculation procedures and Table 41 for acceptable travel rate values.

could be summed or averaged in discrete quantities (short sections) to form a corridor analysis. The relative delay rate or delay ratio can serve as a method to examine congestion levels on the combination of freeways and streets.

Suggested Measures. Average statistics for travel rate and delay rate are useful for intermediate calculations, but may not provide an accurately detailed description of operating conditions and are difficult to interpret or relate to some audiences. Cumulative statistics like **total delay, congested travel,** and **travel time** are more meaningful at this level of analysis. **The relative delay rate, corridor mobility index,** and the **delay ratio** can also be used to compare congestion levels on freeways and arterial streets.

Corridor Example. The Town Avenue and Westside Freeway summary statistics are presented in Table 45 to quantify the corridor congestion level. Total delay, the delay range and congested travel measures are evaluative statistics that are particularly useful in improvement analyses. They identify the magnitude of the problem and point to some solutions that might be studied. The delay per person quantifies a measure of the intensity of congestion, which is more explainable to the public and is close to the way the public perceives congestion levels. The person delay per mile of road is also a useful value for comparing congestion levels on sections of road with varying lengths and varying transit ridership and rideshare activity.

TABLE 45 Town Avenue and Westside Freeway corridor congestion estimate

Location: Suburban
Travel Period: Morning Peak Hour
Travel Direction: Northbound (Peak Direction)
Alternative: Corridor Roadways

Label	Measure	Units	System Element: Town Avenue (Table 44)	System Element: Westside Freeway (Table 43)	Total or Average
a	Length	Miles	8.4	8.4	16.8
d	Vehicle-Miles	Vehicle-Miles	8,527	47,688	56,215
e	Person-Miles	Person-Miles	12,285	62,484	74,769
f	Avg. Vehicle Occup	Persons/Veh	1.44	1.31	1.33
g	Acceptable Travel Rate	Minutes/Mile	2.67	1.30	1.53
j	Actual Travel Rate	Minutes/Mile	5.43	2.68	3.13
k	Actual Travel Speed	Miles/Hour	13	22	21
l	Actual Travel Time	Person-Hours	1,113	2,789	3,902
	Delay Rate				
m	vs. Acceptable	Minutes/Mile	2.77	1.37	1.61
n	vs. Free-Flow	Minutes/Mile	2.96	1.78	1.97
o	Standard Deviation of Actual Travel Rate	Minutes/Mile	0.5	0.5	0.5
	Delay (vs. Acceptable)				
p	Vehicle Travel	Vehicle-Hours	377	1,070	1,447
q	Person Travel	Person-Hours	571	1,431	2,002
	Delay Range				
r	Min. Std. Deviation	Person-Hours	480	910	1,390
s	Max. Std. Deviation	Person-Hours	682	1,952	2,634
	Delay Per:				
t	Person Mile	Person-Minutes	2.8	1.4	1.6
u	Mile of Road	Person-Hours	68	170	154
	Congested Travel				
v	Person-Miles	Person-Miles	12,285	62,484	74,769
w	Person-Hours	Person-Hours	1,113	2,789	3,902
x	Miles of Congested Roadway	Miles	6.3	8.4	14.7
	Relative Congestion Level				
y	Relative Delay Rate	No Units	1.03	1.06	1.06
z	Delay Ratio	No Units	0.51	0.51	0.51
aa	Corridor Mobility Index	No Units	0.38[1]	0.44[1]	0.43

[1] Peak direction lanes—Town Avenue = 2; Westside Freeway = 3.

Note: See Table 40 for calculation procedures and Table 41 for acceptable travel rate values.

More relevant values in comparisons between streets and freeways in a corridor are the **relative delay rate** and the **delay ratio**. Relative comparisons are very important to identifying corridors and facilities within those corridors for improvement studies. The process of combining the modes for a corridor average should not overlook the important modal analyses that must also take place to evaluate individual facilities, since that is the level where many improvements are made, whether those are more lanes, parking spaces, buses, better traffic signal systems, more effective rideshare programs, or access management policies.

The relative delay rate is a comparison of congestion levels to the level of "acceptable" congestion. The values (using the formula in Table 40) can be thought of as the percentage that the actual travel rate is above the acceptable rate. The value is weighted by person-miles of travel and combined into a value for all modes. If the value is 0.65, it takes a traveler 65 percent longer to travel that section of road than the acceptable time for that type of road and the mix of travel modes in the facility. The target value for this measure is 0, which indicates that the actual value and the acceptable value are the same. The range of values can be any value above 0. The values in Table 45 indicate that the freeway is more congested in relation to the acceptable travel conditions.

The delay ratio works in much the same way as the relative delay rate, with the optimal value being 0, although the values of this measure only range between 0 and 1. The delay ratio compares congestion problems to the actual travel rate. Table 45 indicates that the freeway and the street have the same congestion level at two significant digits.

The decision about using these two measures (relative delay rate and delay ratio) will depend on the focus of the analysis. The relative delay rate compares operating conditions to the acceptable "standard" while the delay ratio identifies the magnitude of the mobility problem in relation to operating conditions. Presentation of the information, particularly to nontechnical audiences, will depend on the success of communicating that a value of 0 is a "perfect" situation and how important it is to the audience that the measurement scale has known endpoints. In practice the relative delay rate will have a wider range between the freeway and the street values because of the 0 to 1 scale of the delay ratio. If the weighting for the combined measures is based on person-miles, freeway statistics will also usually dominate the analysis, although that reflects the importance of the highly traveled facilities.

The corridor mobility index is also a comparison technique for different types of facilities and modes. The comparison here is to a very efficient (in **speed** and **vehicle volume**) street or freeway, which would receive a rating of 1. With high volumes of buses or carpools, or higher speeds, the corridor mobility index can exceed 1, while congested facilities or those with a low volume of persons will have a fairly low value. The next section of this chapter provides more detail on when this measure is most useful.

Corridor Improvement Comparisons

New projects, programs or strategies are frequently selected and implemented at the corridor level. Travel time and speed statistics are very useful for single-mode and multimodal comparisons at this level of analysis. The corridor measures that are most useful will vary according to the types of improvements that are examined. Strategies that do not significantly change average vehicle occupancy can be conducted without person travel measures. However, it may be desirable to use a general average vehicle occupancy factor to present the information in person terms if the audience is used to seeing values in that way or if the presenter is trying to educate the audience on those types of measurement techniques.

Town Avenue Examples. Two types of improvements were modeled for the congested section of Town Avenue. An improvement in signal operations is illustrated in Table 46 and the addition of a light rail transit (LRT) line in the median of Town Avenue is illustrated in Table 47. An expanded set of statistics for existing conditions on Town Avenue is included in Table 48. A summary of the statistics in Tables 46, 47, and 48 forms Table 49, which can be used to evaluate the improvements. In general, the light rail line example was prepared to show increases in person travel, vehicle occupancy, transit ridership, and transit travel speed and a decrease in the acceptable delay for transit on Town Avenue. (The index normalizing value [Table 40] for the rail alternative in Table 47 was one street lane). The signal operation improvement example was prepared to show reductions in delay, delay variability, and travel time but not significantly change vehicle occupancy.

The acceptable delay rate decreases more for the signal improvement alternative, but the light rail example also shows a decrease despite the fact that the light rail line has a lower acceptable travel rate than the bus routes. This is because there is a greater number of people using the transit lane, which operates at a lower speed than cars. The increased person movement of the light rail alternative results in a higher level of total delay relative to the acceptable travel rate than either the existing condition or the signal alternative. The signal improvements result in more reliable operations, as illustrated in the smaller range of person-hours of delay. The relative congestion level indicators also show that the signal alternative performed better, reducing the unacceptable delay to one-half the existing level (measured by the relative delay rate), the amount of delay relative to total travel to two-thirds the existing level (measured by the delay ratio) and increasing the corridor mobility index by 60 percent because of both volume and speed increases.

This analysis also illustrates the importance of examining the proper combination of corridor facilities. The light rail alternative had significantly greater person travel than the other two alternatives. This could have been due to new (or induced) demand, but some of the travel also would have transferred from other transit routes or streets. If more roads and transit routes had been included in the analysis, the demand may have remained relatively constant. It may also be that the transit alternative was part of a centralized growth plan and denser development was modeled for the area near Town Avenue. Placing the LRT line in a protected right-of-way would improve corridor mobility, especially if signal improvements are also implemented.

Use of accessibility measures and establishment of an analysis area that includes roads and transit operations that might be significantly affected by the improvement would result in a better comparison of these two alternatives. The corridor mobility index illustrates the main line performance of the facilities but cannot address the added accessibility afforded by transit or intermodal stations.

TABLE 46 Signal operations improvement alternative for Town Avenue

Location: Suburban
Travel Period: Morning Peak Hour
Travel Direction: Northbound (Peak Direction)
Alternative: Signal Improvement

Label	Measure	Units	System Element				Total or Average
			Elm to Maple		Maple to Oak		
			Auto	Bus	Auto	Bus	
a	Length	Miles	2.8	2.8	3.5	3.5	6.3
b	Vehicle Volume	Vehicles	1,200	8	1,300	10	
c	Person Volume	Persons	1,450	250	1,575	300	
d	Vehicle-Miles	Vehicle-Miles	3,360	22	4,550	35	7,967
e	Person-Miles	Person-Miles	4,060	700	5,513	1,050	11,323
f	Avg. Vehicle Occup	Persons/Veh	1.21	31.25	1.21	30.00	1.42
g	Acceptable Travel Rate	Minutes/Mile	2.40	4.00	2.40	4.00	2.65
h	Acceptable Travel Speed	Miles/Hour	25	15	25	15	
i	Free-Flow Travel Rate	Minutes/Mile	2.25	3.50	2.25	3.50	
j	Actual Travel Rate	Minutes/Mile	4.00	6.00	4.00	6.00	4.31
k	Actual Travel Speed	Miles/Hour	15	10	15	10	
l	Actual Travel Time	Person-Hours	271	70	368	105	813
	Delay Rate						
m	vs. Acceptable	Minutes/Mile	1.60	2.00	1.60	2.00	1.66
n	vs. Free-Flow	Minutes/Mile	1.75	2.50	1.75	2.50	1.87
o	Standard Deviation of Actual Travel Rate	Minutes/Mile	0.4	0.6	0.4	0.6	0.4
	Delay (vs. Acceptable)						
p	Vehicle Travel	Vehicle-Hours	89.6	0.7	121.3	1.2	213
q	Person Travel	Person-Hours	108.3	23.3	147.0	35.0	314
	Delay Range						
r	Min. Std. Deviation	Person-Hours	81.2	16.3	110.3	24.5	232
s	Max. Std. Deviation	Person-Hours	135.3	30.3	183.8	45.5	395
	Congested Travel						
v	Person-Miles	Person-Miles	4,060	700	5,513	1,050	11,323
w	Person-Hours	Person-Miles	271	70	368	105	813
	Relative Congestion Level						
y	Relative Delay Rate	No units	0.67	0.50	0.67	0.50	0.64
z	Delay Ratio	No units	0.40	0.33	0.40	0.33	0.39
aa	Corridor Mobility Index	No units	0.51	N/A	0.56	N/A	0.54

N/A—Not applicable. The bus does not travel on a separate facility; the bus statistics are included in the auto value.
Note: See Table 40 for calculation procedures and Table 41 for acceptable travel rate values.

Westside Freeway Examples. The example improvements from Westside Freeway include adding an HOV lane (Table 50), adding one lane and an HOV lane (Table 51) and adding an HOV lane and an incident management program (Table 52). Table 53 summarizes the existing operation of Westside Freeway including the relative congestion statistics. The incident management program alternative was included to show the analysis techniques employed for changes in travel time reliability that come from quickly detecting and removing accidents and vehicle breakdowns, even when there is no significant reduction in usual daily congestion. The HOV lane improvements were added to show the multimodal analysis techniques and evaluation of person movement and speed changes. They assume a high utilization of the HOV lane—a condition that is consistent with the high congestion level on the Westside Freeway, but one that is not encountered in many communities.

Table 54 presents a summary of statistics that are relevant for evaluating the existing operation and the three alternatives. The HOV lane results in lower but still existing congestion, and a reduced range of delay due to the greater reliability of the HOV lane. The relative delay rate and delay ratio are lower, and the corridor mobility index increases above 1, indicating that the combined facility is

TABLE 47 Light rail transit alternative for Town Avenue

Location: Suburban
Travel Period: Morning Peak Hour
Travel Direction: Northbound (Peak Direction)
Alternative: Add Light Rail Transit

Label	Measure	Units	System Element: Elm to Maple: Auto	Elm to Maple: Light Rail	Maple to Oak: Auto	Maple to Oak: Light Rail	Total or Average
a	Length	Miles	2.8	2.8	3.5	3.5	6.3
b	Vehicle Volume	Vehicles	1,000	12	1,200	12	
c	Person Volume	Persons	1,200	700	1,450	750	
d	Vehicle-Miles	Vehicle-Miles	2,800	34	4,200	42	7,076
e	Person-Miles	Person-Miles	3,360	1,960	5,075	2,625	13,020
f	Avg. Vehicle Occup	Persons/Veh	1.20	58.33	1.21	62.50	1.84
g	Acceptable Travel Rate	Minutes/Mile	2.40	4.00	2.40	4.00	2.96
h	Acceptable Travel Speed	Miles/Hour	25	15	25	15	
i	Free-Flow Travel Rate	Minutes/Mile	2.25	4.00	2.25	4.00	
j	Actual Travel Rate	Minutes/Mile	5.00	5.00	6.00	6.00	5.59
k	Actual Travel Speed	Miles/Hour	12	12	10	10	
l	Actual Travel Time	Person-Hours	280	163	508	263	1,213
	Delay Rate						
m	vs. Acceptable	Minutes/Mile	2.60	1.00	3.60	2.00	2.63
n	vs. Free-Flow	Minutes/Mile	2.75	1.00	3.75	2.00	2.73
o	Standard Deviation of Actual Travel Rate	Minutes/Mile	0.5	0.6	0.5	0.6	0.5
	Delay (vs. Acceptable)						
p	Vehicle Travel	Vehicle-Hours	121.3	0.6	252.0	1.4	375
q	Person Travel	Person-Hours	145.6	32.7	304.5	87.5	570
	Delay Range						
r	Min. Std. Deviation	Person-Hours	117.6	13.1	262.2	61.3	454
s	Max. Std. Deviation	Person-Hours	173.6	52.3	346.8	113.8	686
	Congested Travel						
v	Person-Miles	Person-Miles	3,360	1,960	5,075	2,625	13,020
w	Person-Hours	Person-Miles	280	163	508	263	1,213
	Relative Congestion Level						
y	Relative Delay Rate	No units	1.08	0.25	1.50	0.50	1.00
z	Delay Ratio	No units	0.52	0.20	0.60	0.33	0.47
aa	Corridor Mobility Index	No units	0.29	0.34	0.29	0.30	0.30

Note: See Table 40 for calculation procedures and Table 41 for acceptable travel rate values.

more efficient than an optimal freeway lane. The added freeway lane and HOV lane alternative almost eliminate congestion, but the corridor mobility index is not as high as the HOV alternative because the person volume per lane is lower. The incident management alternative also includes lower HOV ridership levels (these might result when travel times are more reliable due to the improvement in incident response), accounting for the lower corridor mobility index, but the relative delay rate and the delay ratio are approximately similar to the HOV lane alternative. The range between minimum and maximum delay in the incident management alternative is lower than for the other systems.

Subareas

Subarea travel time analyses would be governed by the need to collect a sufficient number of travel time data for roads in the subarea. The sampling program would include stratification factors like facility type and traffic volume range to minimize variation among roadways and reduce sample sizes. A statistically reliable sample size for estimating the number of segments required should be based on travel time variability among segments, the permitted relative error, and the confidence level of the estimate. The sample size can be computed using the normal distribution as

TABLE 48 Summary of existing Town Avenue congestion statistics

Location: Suburban
Travel Period: Morning Peak Hour
Travel Direction: Northbound (Peak Direction)
Alternative: Existing Operations

Label	Measure	Units	System Element: Elm to Maple: Auto	Elm to Maple: Bus	Maple to Oak: Auto	Maple to Oak: Bus	Total or Average
a	Length	Miles	2.8	2.8	3.5	3.5	6.3
d	Vehicle-Miles	Vehicle-Miles	2,800	22	4,200	35	7,057
e	Person-Miles	Person-Miles	3,360	700	5,075	1,050	10,185
f	Avg. Vehicle Occup	Persons/Veh	1.20	31.25	1.21	30.00	1.44
g	Acceptable Travel Rate	Minutes/Mile	2.40	4.00	2.40	4.00	2.67
j	Actual Travel Rate	Minutes/Mile	5.00	7.50	6.00	8.57	6.04
l	Actual Travel Time	Person-Hours	280	88	508	150	1,025
	Delay Rate						
m	vs. Acceptable	Minutes/Mile	2.60	3.50	3.60	4.57	3.36
n	vs. Free-Flow	Minutes/Mile	2.75	4.00	3.75	5.07	3.57
o	Standard Deviation of Actual Travel Rate	Minutes/Mile	0.5	0.7	0.5	0.7	0.5
	Delay (vs. Acceptable)						
p	Vehicle Travel	Vehicle-Hours	121.3	1.3	252.0	2.7	377
q	Person Travel	Person-Hours	145.6	40.8	304.5	80.0	571
	Delay Range						
r	Min. Std. Deviation	Person-Hours	117.6	32.7	262.2	67.8	480
s	Max. Std. Deviation	Person-Hours	173.6	49.0	346.8	92.3	662
	Congested Travel						
v	Person-Miles	Person-Miles	3,360	700	5,075	1,050	10,185
w	Person-Hours	Person-Miles	280	88	508	150	1,025
	Relative Congestion Level						
y	Relative Delay Rate	No units	1.08	0.88	1.50	1.14	1.28
z	Delay Ratio	No units	0.52	0.47	0.60	0.53	0.56
aa	Corridor Mobility Index	No units	0.35	N/A	0.35	N/A	0.35

N/A—Not applicable. The bus does not travel on a separate facility; the statistics are included in the auto value.
Note: See Table 40 for calculation procedures and Table 41 for acceptable travel rate values.

outlined in Equations 22 and 23 and making appropriate reductions for finite populations in each section.

The resulting sample indicates the number of roadway segments within a stratum (e.g., freeways, arterials, CBD streets) within the subarea that require direct travel time data collection. These segments should be randomly chosen from different routes in each stratum, and they should be representative of typical roadways within the subarea. Travel times for the remaining segments that are not sampled can be estimated by applying the results from sections with data collection. Segments with similar traffic volume and roadway characteristics would be grouped, and the congestion statistics (e.g., delay) for the section with direct data collection increased to account for the segments without data collection. In addition, "bottleneck" sections (where traffic volumes are not indicative of operating speeds) should be studied individually.

The collected data can also be used to assist local agencies in calibrating or adjusting the surrogate estimation equations presented in this report and elsewhere to local operating conditions.

Suggested Measures. Average statistics for travel rate and delay rate are useful for intermediate calculations, but they may not provide an accurately detailed description of operating conditions within a subarea. Cumulative statistics like

TABLE 49 Example of project selection summary for Town Avenue

Location: Suburban
Travel Period: Morning Peak Hour
Travel Direction: Northbound (Peak Direction)
Alternative: Improvement Summary

Label	Measure	Units	Improvement Alternative		
			Existing (Table 48)	Signal Improvement (Table 46)	Light Rail Transit (Table 47)
a	Length	Miles	6.3	6.3	6.3
d	Vehicle-Miles	Vehicle-Miles	7,057	7,967	7,076
e	Person-Miles	Person-Miles	10,185	11,323	13,020
f	Avg. Vehicle Occup	Persons/Veh	1.44	1.42	1.84
g	Acceptable Travel Rate	Minutes/Mile	2.67	2.65	2.96
j	Actual Travel Rate	Minutes/Mile	6.04	4.31	5.59
l	Actual Travel Time	Person-Hours	1,025	813	1,213
	Delay Rate				
m	vs. Acceptable	Minutes/Mile	3.36	1.66	2.63
n	vs. Free-Flow	Minutes/Mile	3.57	1.87	2.73
o	Standard Deviation of Actual Travel Rate	Minutes/Mile	0.5	0.4	0.5
	Delay (vs. Acceptable)				
p	Vehicle Travel	Vehicle-Hours	377	213	375
q	Person Travel	Person-Hours	571	314	570
	Delay Range				
r	Min. Std. Deviation	Person-Hours	480	232	454
s	Max. Std. Deviation	Person-Hours	662	395	686
	Relative Congestion Level				
y	Relative Delay Rate	No units	1.28	0.64	1.00
z	Delay Ratio	No units	0.56	0.39	0.47
aa	Corridor Mobility Index	No units	0.35	0.54	0.30

Note: See Table 40 for calculation procedures and Table 41 for acceptable travel rate values.

total delay, congested travel, and **congested roadway** are more meaningful at this level of analysis. These measures are calculated in the same manner as in the corridor analysis, with subtotals for measures calculated for each route within the subarea.

Regional Networks

Regional analyses should be governed by many of the same needs as those on a subarea basis. Sampling programs would be required to collect statistically valid data on a limited number of roadways, and stratification factors would be used to minimize variation among roadways and reduce sample sizes. Cost-effective data collection techniques should be considered because of the large data collection requirements and limited financial resources typical of most large urban areas. Where bottlenecks and points of recurrent congestion are known, they should be measured in addition to the samples.

Suggested Measures. Some congestion statistics are useful in areawide analyses, but at the regional level the questions asked of the transportation analyses often require a broader set of answers. Displaying these statistics will require the analyst to mix a variety of facility specific and regional summary values. Table 55 presents a summary of the information that might be used for corridor, subarea, and areawide analyses. The level of information would vary depending on the analysis being performed, but the measures are selected to support the types of evaluations and decisions typically made at each level. As noted in the corridor-level discussion, the use of facility- or mode-specific analyses is more appropriate than regional analyses. Accessibility measures become more important as the analysis area is widened or the modal coverage expands.

Average statistics for travel rate and delay rate are useful for intermediate areawide calculations but most likely will not provide an accurately detailed description of operating conditions within a regional network. Cumulative statistics like **total delay, congested travel,** and **congested roadway** are more meaningful at the regional level of analysis. These measures are calculated in the same manner as in the corridor analysis, with subtotals for measures being calculated for

TABLE 50 HOV lane alternative for Westside Freeway

Location: Suburban
Travel Period: Morning Peak Hour
Travel Direction: Northbound (Peak Direction)
Alternative: Add 1 HOV Lane

Label	Measure	Units	System Element: 1st to 8th: Auto	System Element: 1st to 8th: HOV	System Element: 8th to 15th: Auto	System Element: 8th to 15th: HOV	Total or Average
a	Length	Miles	4.4	4.4	4.0	4.0	8.4
b	Vehicle Volume	Vehicles	5,800	1,200	5,500	1,200	
c	Person Volume	Persons	6,100	4,000	5,800	4,000	
d	Vehicle-Miles	Vehicle-Miles	25,520	5,280	22,000	4,800	57,600
e	Person-Miles	Person-Miles	26,840	17,600	23,200	16,000	83,640
f	Avg. Vehicle Occup	Persons/Veh	1.05	3.33	1.05	3.33	1.45
g	Acceptable Travel Rate	Minutes/Mile	1.33	1.00	1.33	1.00	1.20
h	Acceptable Travel Speed	Miles/Hour	45	60	45	60	
i	Free-Flow Travel Rate	Minutes/Mile	0.90	0.90	0.90	0.90	
j	Actual Travel Rate	Minutes/Mile	2.40	0.92	3.00	0.92	1.97
k	Actual Travel Speed	Miles/Hour	25	65	20	65	
l	Actual Travel Time	Person-Hours	1,074	271	1,160	246	2,751
	Delay Rate						
m	vs. Acceptable	Minutes/Mile	1.07	0.00	1.67	0.00	0.80
n	vs. Free-Flow	Minutes/Mile	1.50	0.02	2.10	0.02	1.07
o	Standard Deviation of Actual Travel Rate	Minutes/Mile	0.5	0.1	0.5	0.1	0.3
	Delay (vs. Acceptable)						
p	Vehicle Travel	Vehicle-Hours	453.7	0.0	611.1	0.0	1,065
q	Person Travel	Person-Hours	477.2	0.0	644.4	0.0	1,122
	Delay Range						
r	Min. Std. Deviation	Person-Hours	253.5	0.0	451.1	0.0	705
s	Max. Std. Deviation	Person-Hours	700.8	29.3	837.8	26.7	1,595

Note: See Table 40 for calculation procedures and Table 41 for acceptable travel rate values.

each route (and possibly subarea) within the regional network.

Table 55 shows that individual mode or facility analyses are used to "build up" to the areawide statistics and can be used in conjunction with areawide analyses. Average vehicle occupancy and daily VMT per lane-mile can be used to evaluate the effect of some types of improvements but are not sufficient for all.

Analyzing all facilities in an area (in the second group of values) requires summary statistics, but other statistics can also provide information depending on the type of analysis and improvements being studied. Congested travel and facility miles are useful summaries of conditions and can be presented as either (or both) relative to the acceptable measures for areawide studies, or relative to an absolute value such as free-flow travel for national or state "needs" studies.

Accessibility measures are highlighted in Table 55 because they focus on the basic reason for having transportation systems at all: allowing achievement of travel objectives. They measure performance of the transportation system, and its interaction with land use, in how well travel objectives are met.

Accessibility measures allow the travel time focus of travelers and shoppers, and the need that agencies have to identify facilities that need improvements, to be combined into the number and percentage of potential travel objectives reachable within acceptable time limits. The results of this analysis can identify areas and subareas in which some type of improvement is needed. The effect of a broad range of construction, operation, policy, or land use pattern changes can be identified with accessibility measures. Pricing actions that affect demand and travel patterns also change travel time and accessibility.

A few typical trip purposes are illustrated in Table 55, but others also could be used. The measure of "percent of children within acceptable time of school" was included for a simple illustration of travel market stratification, but the example equally well could have been "percent of commerce (quantified on the basis of employment) within acceptable time of freight distribution centers."

TABLE 51 HOV and general purpose lane addition alternative for Westside Freeway

Location: Suburban
Travel Period: Morning Peak Hour
Travel Direction: Northbound (Peak Direction)
Alternative: Add 1 HOV Lane and 1 General Lane

Label	Measure	Units	System Element				Total or Average
			1st to 8th		8th to 15th		
			Auto	HOV	Auto	HOV	
a	Length	Miles	4.4	4.4	4	4	8.4
b	Vehicle Volume	Vehicles	7,000	750	7,000	750	
c	Person Volume	Persons	8,000	2,000	8,000	2,000	
d	Vehicle-Miles	Vehicle-Miles	30,800	3,300	28,000	3,000	65,100
e	Person-Miles	Person-Miles	35,200	8,800	32,000	8,000	84,000
f	Avg. Vehicle Occup	Persons/Veh	1.14	2.67	1.14	2.67	1.29
g	Acceptable Travel Rate	Minutes/Mile	1.33	1.00	1.33	1.00	1.27
h	Acceptable Travel Speed	Miles/Hour	45	60	45	60	
i	Free-Flow Travel Rate	Minutes/Mile	0.90	0.90	0.90	0.90	
j	Actual Travel Rate	Minutes/Mile	1.58	0.92	1.50	0.92	1.42
k	Actual Travel Speed	Miles/Hour	38	65	40	65	
l	Actual Travel Time	Person-Hours	926	135	800	123	1,985
	Delay Rate						
m	vs. Acceptable	Minutes/Mile	0.25	0.00	0.17	0.00	0.17
n	vs. Free-Flow	Minutes/Mile	0.68	0.02	0.60	0.02	0.52
o	Standard Deviation of Actual Travel Rate	Minutes/Mile	0.5	0.1	0.5	0.1	0.4
	Delay (vs. Acceptable)						
p	Vehicle Travel	Vehicle-Hours	126.1	0.0	77.8	0.0	204
q	Person Travel	Person-Hours	144.1	0.0	88.9	0.0	233
	Delay Range						
r	Min. Std. Deviation	Person-Hours	0.0	0.0	0.0	0.0	0
s	Max. Std. Deviation	Person-Hours	437.4	14.7	355.6	13.3	821

Note: See Table 40 for calculation procedures and Table 41 for acceptable travel rate values.

These analyses can be conducted for either individual improvements or areawide strategies, although they are more effective at the corridor, subarea, or areawide strategy level. As noted in Table 55, accessibility measures are normally calculated for each small area (traffic analysis zone) within the corridor, subarea, or region being examined, taking into account all of the opportunities for meeting travel objectives within the region as a whole. Maps of the zone by zone results are very instructive in identifying who is most in need and who is most helped by a particular improvement. Zonal level results can be accumulated for the corridor, subarea, or region as a summary measure, using weighted averages where appropriate.

A limitation is that the magnitude of existing land development and transportation facilities tends to overwhelm the effect of any new improvements. This causes accessibility measures to represent current features more than the changes accruing from new developments, especially where the new development is focused on achieving a different set of goals. This problem can be addressed by calculating the change in "no-build" alternative. This change will be attributable to the new developments and/or transportation facilities under analysis. This approach will help identify those developments and improvements that contribute to achieving areawide goals for acceptable travel times and accessibility.

Concerns about the effect of "urban sprawl" can be addressed using accessibility measures. Several different areawide development scenarios can be tested and presented to citizens in a format that can be readily understood. Current and future travel conditions as described by measures such as those in Table 55 can be noted, along with such characteristics as percent of trips by mode, the cost of new facilities or operating strategies and land use patterns. This type of information is much better than the statistics that are currently presented for review in public discussions of long-range planning options. Accessibility measures and associated maps and graphics give transportation and land use professionals a method to provide citizens with an idea of the impact of their choices.

TABLE 52 HOV and incident management alternative for Westside Freeway

Location: Suburban
Travel Period: Morning Peak Hour
Travel Direction: Northbound (Peak Direction)
Alternative: Incident Management Program and HOV Lane

Label	Measure	Units	System Element				Total or Average
			1st to 8th		8th to 15th		
			Auto	HOV	Auto	HOV	
a	Length	Miles	4.4	4.4	4	4	8.4
b	Vehicle Volume	Vehicles	5,800	1,000	5,500	1,000	
c	Person Volume	Persons	6,100	3,000	5,800	3,000	
d	Vehicle-Miles	Vehicle-Miles	25,520	4,400	22,000	4,000	55,920
e	Person-Miles	Person-Miles	26,840	13,200	23,200	12,000	75,240
f	Avg. Vehicle Occup	Persons/Veh	1.05	3.00	1.05	3.00	1.35
g	Acceptable Travel Rate	Minutes/Mile	1.33	1.00	1.33	1.00	1.22
h	Acceptable Travel Speed	Miles/Hour	45	60	45	60	
i	Free-Flow Travel Rate	Minutes/Mile	0.90	0.90	0.90	0.90	
j	Actual Travel Rate	Minutes/Mile	2.22	0.92	2.86	0.92	1.98
k	Actual Travel Speed	Miles/Hour	27	65	21	65	
l	Actual Travel Time	Person-Hours	994	203	1,105	185	2,487
	Delay Rate						
m	vs. Acceptable	Minutes/Mile	0.89	0.00	1.52	0.00	0.79
n	vs. Free-Flow	Minutes/Mile	1.32	0.02	1.96	0.02	1.08
o	Standard Deviation of Actual Travel Rate	Minutes/Mile	0.2	0.1	0.2	0.1	0.2
	Delay (vs. Acceptable)						
p	Vehicle Travel	Vehicle-Hours	378.1	0.0	558.7	0.0	937
q	Person Travel	Person-Hours	397.6	0.0	589.2	0.0	987
	Delay Range						
r	Min. Std. Deviation	Person-Hours	308.2	0.0	511.9	0.0	820
s	Max. Std. Deviation	Person-Hours	487.1	22.0	666.5	20.0	1,196

Note: See Table 40 for calculation procedures and Table 41 for acceptable travel rate values.

The use of accessibility measures will mean more computer-based analyses, which might be perceived as a move away from direct measurement of congestion for some levels of analysis. This does not mean that travel time data will be less useful, or less cost-effective to collect. On the contrary, direct measurement of travel time can be used not only to quantify existing conditions but also to calibrate wide-scale models of traffic and transportation system operation and to perform corridor and facility analyses. Geographic information systems are being used to calculate accessibility measures based on planning model travel time and speed output statistics. The typical sequence of events leading up to a public discussion of the alternative improvement plans might be

1. Collecting existing traffic condition data directly.
2. Calculating measures.
3. Comparing results to acceptable conditions that are determined from public comments during long-range plan discussion.
4. Identifying areas or modes that need improvement.
5. Proposing solutions—areawide strategies will guide which specific improvements are tested.
6. Testing areawide improvements.
7. Estimating accessibility, mobility, and congestion measures for each strategy or alternative.
8. Comparing measures to goals.
9. Evaluating and selecting for inclusion in the plan individual mode or facility improvements that fit with the areawide strategy.

A CONGESTION INDEX CONCEPT

It is difficult to address nontechnical audiences without meaningful summary congestion statistics. This difficulty has led many to suggest the need for a congestion index. Existing measures such as the Congestion Severity Index, Roadway Congestion Index, and Lane-Mile Duration Index described in this report have been used to estimate different aspects of congestion. This section includes a description of several key elements of an index and a concept that may be a basis for a generally accepted congestion index.

TABLE 53 Summary of existing Westside Freeway congestion statistics

Location: Suburban
Travel Period: Morning Peak Hour
Travel Direction: Northbound (Peak Direction)
Alternative: Existing Operations

Label	Measure	Units	System Element				Total or Average
			1st to 8th		8th to 15th		
			Auto	Bus	Auto	Bus	
a	Length	Miles	4.4	4.4	4.0	4.0	8.4
d	Vehicle-Miles	Vehicle-Miles	25,520	88	22,000	80	47,688
e	Person-Miles	Person-Miles	30,624	2,860	26,400	2,600	62,484
f	Avg. Vehicle Occup	Persons/Veh	1.20	32.50	1,20	32.50	1.31
g	Acceptable Travel Rate	Minutes/Mile	1.33	1.00	1.33	1.00	1.30
j	Actual Travel Rate	Minutes/Mile	2.40	2.40	3.00	3.00	2.68
l	Actual Travel Time	Person-Hours	1,225	114	1,320	130	2,789
	Delay Rate						
m	vs. Acceptable	Minutes/Mile	1.07	1.40	1.67	2.00	1.37
n	vs. Free-Flow	Minutes/Mile	1.50	1.50	2.10	2.10	1.78
o	Standard Deviation of Actual Travel Rate	Minutes/Mile	0.5	0.5	0.5	0.5	0.5
	Delay (vs. Acceptable)						
p	Vehicle Travel	Vehicle-Hours	453.7	2.1	611.1	2.7	1,070
q	Person Travel	Person-Hours	544.4	66.7	733.3	86.7	1,431
	Delay Range						
r	Min. Std. Deviation	Person-Hours	289.2	42.9	513.3	65.0	910
s	Max. Std. Deviation	Person-Hours	799.6	90.6	953.3	108.3	1,952
	Relative Congestion Level						
y	Relative Delay Rate	No units	0.80	0.00	1.25	0.00	0.92
z	Delay Ratio	No units	0.44	0.00	0.56	0.00	0.45
aa	Corridor Mobility Index	No units	0.51	N/A	0.39	N/A	0.45

N/A—Not applicable. The bus does not travel on a separate facility; the statistics are included in the auto value.
Note: See Table 40 for calculation procedures and Table 41 for acceptable travel rate values.

The most desirable characteristic of an index is the communication of the congestion level in terms that are easily understood. For this to occur, the index must include concepts that are familiar and the index must readily illustrate the magnitude of the problem in relation to the desirable condition. The level-of-service measure performs this function for relatively short sections of the roadway network with letter grades familiar to most people. The Roadway Congestion Index (*36*) uses daily volume per lane-mile values and a comparative value so that index values in excess of 1 represent undesirable areawide congestion levels. These two different analysis procedures (level-of-service and Roadway Congestion Index) are difficult to compare to each other, but they represent practices that have proven their worth.

Other important factors that should be included in an index concept are the ability to accommodate several different facilities or modes with a common measure and the use of a continuous numerical scale that can be used for all analysis area, facility, and mode combinations. These two factors are discussed below in relation to the report recommendations for analytic and communication improvements for congestion information.

The common measure that appears to fit the needs of agencies and travelers alike is based on travel rate, travel speed, or travel time. Different performance expectations can be incorporated into the index for freeways and arterial streets, for example, and modified by the acceptable travel conditions for each area.

The use of a continuous numerical scale will adjust a shortcoming in the level-of-service technique that uses (discrete) letter grades. Letter grades are easy to communicate, but the calculation procedures can produce some discontinuities where the next letter grade is only 10 vehicles from the current volume. This "jump" in grade can be remedied with a numerical scale. A numerical scale can also provide a method to weight the conditions in adjacent freeways and HOV lanes or rail lines to obtain a corridor value. The corridor values can be computed for hourly conditions and weighted by the number of travelers to estimate peak-period or daily index values.

TABLE 54 Westside Freeway improvement project summary

Location: Suburban
Travel Period: Morning Peak Hour
Travel Direction: Northbound (Peak Direction)
Alternative: Improvement Summary

Label	Measure	Units	Improvement Alternative			
			Existing (Table 53)	Add HOV Lane (Table 50)	Add 1 Lane and HOV Lane (Table 51)	Incident Mgmt and HOV (Table 52)
a	Length	Miles	8.4	8.4	8.4	8.4
d	Vehicle-Miles	Vehicle-Miles	47,688	57,600	65,100	55,920
e	Person-Miles	Person-Miles	62,484	83,640	84,000	75,240
f	Avg. Vehicle Occup	Persons/Veh	1.31	1.45	1.29	1.35
g	Acceptable Travel Rate	Minutes/Mile	1.30	1.20	1.27	1.22
j	Actual Travel Rate	Minutes/Mile	2.68	1.97	1.42	1.98
l	Actual Travel Time	Person-Hours	2,789	2,751	1,985	2,487
	Delay Rate					
m	vs. Acceptable	Minutes/Mile	1.37	0.80	0.17	0.79
n	vs. Free-Flow	Minutes/Mile	1.78	1.07	0.52	1.08
o	Standard Deviation of Actual Travel Rate	Minutes/Mile	0.5	0.3	0.4	0.2
	Delay (vs. Acceptable)					
p	Vehicle Travel	Vehicle-Hours	1,070	1,065	204	937
q	Person Travel	Person-Hours	1,431	1,122	233	987
	Delay Range					
r	Min. Std. Deviation	Person-Hours	910	705	0	820
s	Max. Std. Deviation	Person-Hours	1,952	1,595	821	1,196
	Relative Congestion Level					
y	Relative Delay Rate	No units	0.92	0.60	0.12	0.59
z	Delay Ratio	No units	0.45	0.30	0.11	0.31
aa	Corridor Mobility Index	No units	0.45	1.05	0.71	0.78

Note: See Table 40 for calculation procedures and Table 41 for acceptable travel rate values.

Basic Concept

The congestion index should reflect motorists' perceptions of congestion on the roadway they travel. It seems desirable, therefore, to base this ratio on the relative speed change on any roadway between congested and free-flow conditions. Thus, the same index could be applied to various roadway types with different free-flow speeds. A freeway that reduces speed from 60 to 30 mph (50 percent decline in speeds) would have the same "index" as an arterial street where speeds drop from 30 to 15 mph.

When a freeway's speeds drop by 50 percent from 60 to 30 mph, the index value can be 5 and, in turn, if the freeway is stopped, the 100 percent decline in speed would be assigned a value of 10. The index becomes the percentage drop in speeds divided by 10.

The resulting line for all roadway types is shown in Figure 17. The percentage decrease in speed is plotted on the X axis, and the speed reduction index is plotted on the Y axis. Illustrative applications of this index are shown in Table 56. The index clearly defines the intensity of congestion, since most values of 5 or more reflect congested operations.

Application of the Speed Reduction Index

The speed reduction index can be applied to individual facility segments, entire routes, or an entire urban area. It may apply for both peak and off-peak conditions. Application requires identifying the baseline conditions from which the time losses are established. One possibility is to use free-flowing speeds as representative of uncongested conditions. Alternatively, travel times during specified "uncongested" hours of the day—i.e., 10 to 11 a.m. or 9 to 10 p.m., could serve as the benchmark from which "congested" (i.e., peak period) conditions could be compared.

A community could establish the acceptable levels of the congestion index for various facilities and time periods. Area goals and development policies, as reflected by such documents as the transportation improvement program and the long-range plan, should be used to identify the level of con-

TABLE 55 Summary of performance measures for corridors, subareas, and regions

Measure	Corridor	Sub-Area or Sub-Region	Region or Urban Area
For Each Functional Class or Mode			
Lane-miles of road	NP		
Daily VMT (1000)	NP		
Daily PMT (1000)	NP		
Average vehicle occupancy	P	P	P
Number of daily person trips	NP		
Daily VMT/Lane-mile	P	P	P
For all Facilities			
Congested PMT (1000)	S	S	S
% of Daily PMT	P	P	P
Congested lane-miles	S	S	S
% of total system	P	P	P
Delay rate (minutes/mile)	P	S	S
Total delay (person-hours)	P	P	P
Delay range (person-hours)	P	S	S
Minimum			
Maximum			
Relative congestion level			
Relative delay rate	P	S	S
Delay ratio	P	S	S
Corridor mobility index	P	S	S
Accessibility Measures			
Travel objectives within acceptable travel time			
Jobs within acceptable travel time (of persons)	P*	P*	P*
% of jobs within acceptable time (of persons)	P*	P*	P*
Area within acceptable travel time of shopping	P*	P*	P*
Area within acceptable travel time of school	P*	P*	P*
Weighted average % of jobs within acceptable time	P	P	P
% of persons within acceptable time of shopping	P	P	P
% of children within acceptable time of school	P	P	P
% of persons within 30 minutes (during peak period) of:			
Central business district		S	P
Airport		S	P
Major activity center		P	P

Note: All congestion levels compared to acceptable travel values (e.g., Table 41); see Table 40 for calculation procedures and Table 41 for acceptable travel rate values.

NP—Not a performance measure.
P—Primary performance measure.
S—Secondary performance measure.
*—Calculated and displayed for each small analysis area within the corridor, sub-area or region on the basis of all opportunities within the region for travel objective fulfillment.

gestion that is acceptable for individual facilities, corridors, subareas, or areas. The ratio of an existing index value to the acceptable index value will illustrate areas of concern. Congestion index values can be computed for the range of analysis levels from individual facilities to areawide networks and for various time periods.

Speed reduction index values for more than one facility should be combined as weighted averages, rather than addition or simple averages. The weighting parameters would usually be persons or vehicles. The weighted averages could also be constructed with the ratio of index value to acceptable index value. This would illustrate areas where travel conditions are worse than desired. If the person volume were significant on those congested facilities, the index ratio value for a corridor or region would be worse than areas where a few minor problems existed.

A speed reduction index concept has several important benefits. It provides more information on the magnitudes of congestion in severely congested operating conditions than the traditional level-of-service concept. It also provides a value that is easy to use and understand. A continuous scale with numerical values from 0 to 10 may be more useful for some

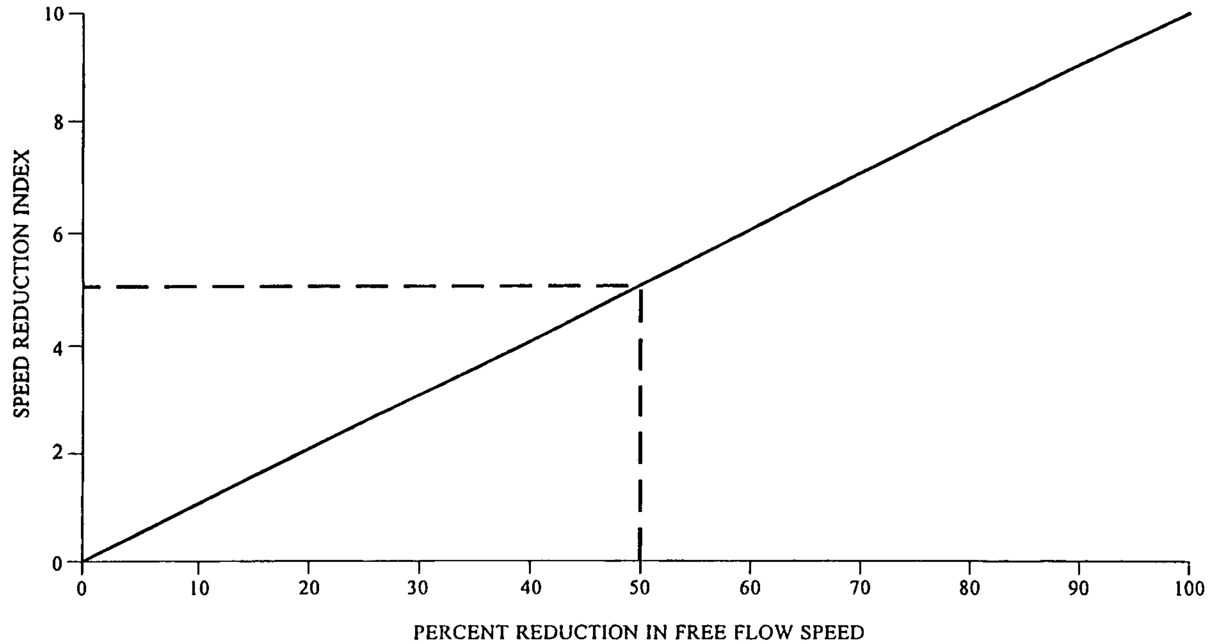


Figure 17. Speed reduction index.

nontechnical audiences than actual delay, travel rate, or speed values. An index that provides numerical values from 0 to 10 is useful for both technical and nontechnical audiences. The continuous numerical scale also remedies some of the problems related to the discrete letter grades of the level-of-service concept where small changes in volume can change the LOS designation when they occur near a boundary.

The expansion of the description of very congested conditions (analogous to an expanded level-of-service F) is a particularly useful feature for a variety of analyses. California has used F numbers to indicate duration of LOS F conditions. The speed reduction index can illustrate both duration and intensity of very congested traffic conditions. The congestion level identified as undesirable can be customized for local decision-making purposes and varied by location, facility or mode type, and other factors.

The index might be used to prioritize sections of a transportation network for improvement or study. It also may be expanded to include other travel modes and delay relative to locally determined acceptable travel rate values. Practition-

TABLE 56 Illustrative application of the speed reduction index

Roadway	Direction and Peak Hour	Free-Flow Speed (midday mph)	Peak Hour Speed	Ratio[1]	% Reduction[2]	Speed Reduction Congestion Index[3]
I-95 George Washington Bridge, NY	EB A.M.	45	5	0.11	89	8.8
I-95, Westport-Bridgeport, CT	EB P.M.	60	20	0.33	67	6.7
I-95, Quinnipiac River Bridge, New Haven, CT	EB A.M.	45	26	0.58	42	4.2
I-10 Katy Freeway Houston, TX						
Mainlanes	WB P.M.	60	29	0.48	52	5.2
HOV Lane	WB P.M.	60	55	0.92	8	0.8
Mainlane and HOV Lane	WB P.M.	60				
Westheimer Road, Houston, TX	EB P.M.	35	20	0.57	43	4.3

1 Ratio of peak-hour speed to free-flow speed.
2 Percent reduction in free-flow speed.
3 See Figure 17. Also Index = % Reduction divided by 10.

ers might use the index to communicate the differences in congestion level on portions of the system in an area, and decision makers or policy boards may relate areawide transportation goals to an index value.

The speed reduction index could be used in a range of situations from individual sections of road to corridors, subregions, or urban areas. It can be used as input to congestion management systems. The index values can be weighted with person volume for several facilities in the analysis to produce an areawide illustration of congestion. The amount of person travel that occurs in conditions worse than the locally desirable standards can be used to monitor progress toward transportation goals and identify problem areas.

The concept described here can be advanced beyond this initial stage and extended to other modes of travel. This will require information on the relative expectation that travelers, residents, and businesses have for travel modes and roadway classes.

CHAPTER 5

CONCLUSIONS AND SUGGESTED RESEARCH

CONGESTION MEASUREMENT IMPLICATIONS

The growing emphasis on congestion management calls for parallel emphasis on congestion measurement. Communities should be encouraged to conduct more travel time studies, not only on particular routes, but to assess on a regional scale the locations and extent of congestion. Peak and off-peak travel time contours, from the city center, airport, or other major activity complex, for example, can produce easily obtainable indices of congestion. When the studies are conducted annually, trends in both congestion and mobility can be identified.

It is clear that travel time–based measures are the most appropriate way to assess congestion. These measures will best satisfy the information needs of a variety of audiences and the requirements for a range of analyses.

Transportation professionals will continue to be major users of congestion estimation techniques, but an increasing array of policy, public information, and media uses will be part of the environment under which analyses will be prepared. If this wider group of audiences is combined with the expanded list of construction, operation, and policy or program improvements that might be pursued to address mobility and accessibility problems in the transportation system, the use of travel time–based measures has a greater opportunity of providing the information required than any alternative. This means not that vehicle volume and capacity measures are less valid or not useful, but that their use will be focused on a subset of congestion measurement needs that will vary according to the urban area, nature of the problem, and the scope of the improvement.

Quantifying Congestion

Congestion measures should focus on the attributes that represent the targets of the transportation system, namely the movement of people, goods, and information from an origin to a destination. The attribute of transportation facilities that is most easily communicated to the widest audience is that of travel time. It is used by most travelers in deciding the route, mode, and time of departure for trips, and is used by businesses and residents for those decisions as well as for business, housing, or development location decisions. It is useful in a broad set of contexts including facility construction or expansion, transit fleet expansion, operational improvements, transit schedule development, analysis of modal alternatives, impact of land use decisions, and the effect of demand management programs. These analyses can be expressed in people or tons; they can have an analysis term of between now and 50 years from now; they can focus on the effect of one or multiple travel modes, the effect of travel reduction programs, or alternative land use patterns; and they can be designed for planners and engineers or the general public. Therefore, this research has focused on quantifying congestion in measuring or estimating travel times.

The congestion measurement techniques used to address these needs can be categorized in several ways.

Data Collection. One characteristic is the method used to obtain the data. Direct measures are those derived from observations of conditions. Surrogate or indirect measures are used when no existing condition is present, where data collection resources prohibit direct data collection, where required for consistency (as in future analyses or examinations of alternatives) between conditions that cannot be measured, or where large-scale policy assessments are needed.

Congestion Comparison. A crucial distinguishing characteristic of congestion measures is whether the value is compared to free-flow conditions or to some agreed-upon value of acceptable speed or travel rate. In most cases, the free-flow value is used in an analysis of "needs" or comparison to "ideal" conditions or "standards." The free-flow comparison is useful in a variety of baseline procedures where a common reference point is needed.

The use of "acceptable" speed, travel rate, or travel time is useful when related to financially or physically constrained improvement programs. If congestion cannot be eliminated, it is more useful to know the amount of "congestion" (as it would be defined relative to free-flow conditions) that is acceptable after the improvement has been made.

This concept is also useful in urban regions or states where multimodal considerations are an integral component of the analysis. For HOV lanes, transit improvements and a variety of travel demand management solutions to encourage mode shifts away from single occupant vehicles, a certain amount of congestion is desirable. The "acceptable" travel speed or rate is a way for this consideration to be quantified in the analysis of alternatives and in project selection.

Reliability. Absolute or relative congestion level is important in most analyses, but the variation in travel time is often an important part of the users' decision-making process and should be quantified in system analyses. Some improvement alternatives (e.g., incident detection and response programs) may have little effect on the usual congestion level, but they increase the reliability of the system. This is particularly important for manufacturers and freight transporters.

Incorporating Citizen Input. The recommendations of this project are focused on measuring and presenting congestion in forms that are easily used and widely understood. The level-of-service concept has served this purpose well for many years, but travel time and speed measures will be more useful for some types of analysis. The important part of measurement selection is that there should be a direct relationship between the system goals that are expressed by the users and the techniques used to select projects or strategies designed to achieve those goals. If citizens are able to see the impact of their proposed system investments, they will be able to provide more detailed input on the tradeoffs facing transportation and land-use planning agencies.

Data Collection and Analysis

The data collection and development of performance measures for this research project focused on roadway congestion. This focus did not change the requirements for congestion measurements, however, and the research developed a description of the wider set of needs before proceeding with the development of roadway congestion measurement techniques and data collection guidelines. The approach to measurements resulted in a data collection and analysis system that will work much better in the future than it will for many current applications. **Direct collection of travel time data is a priority item for complete implementation of a suggested congestion measurement system.** The research also identified several methods to address the short-term data collection problems, some of which rely on existing roadway capacity measurement techniques.

If direct travel speed data collection is used by agencies, the travel data contained in this study will provide a framework for estimating the number of observations and the number of roadway segments to be included in the data collection effort. The key to a manageable data collection effort is the stratification of the roadway segments to reduce the amount of expected variability in travel speed on each segment of a group. The reduction in data collection requirements achieved using a stratified process is substantial. A 50 percent to 60 percent reduction in the number of street segments can be expected using a stratified random sampling process.

The size and cost of direct data collection will depend on the level of confidence or prediction required, the allowable error for the application, and the variability of the particular data element. The variability in the element is an inherent quantity and cannot be altered, but that variability can be managed using the stratification procedures. In many cases, however, agencies or individuals with measurement programs can determine the level of confidence and prediction error that is allowable. They can thereby exert control over the level and type of data collection required to generate estimates of congestion.

An alternative to full-scale direct measurement of travel speed is using traditional traffic count–based analysis procedures such as aerial photography or field reconnaissance observations to identify corridors where congestion is a problem and then targeting the travel time data collection in those areas. The travel-time collection procedures can enable the analyst to estimate congestion levels, identify bottleneck locations requiring additional study, develop benefit information for alternative improvements, and provide a communication medium with a range of audiences.

The research also analyzed data collected by agencies throughout the United States. This information was used in several ways. The data were used to supplement data collected by the research team for the purposes of identifying the variability of travel speed and the stratification boundaries for data collection and analysis. The conclusions from this effort are summarized in Chapter 2. The variation in predicted travel speeds identified in the research may not be sufficient for some agencies and uses; some suggestions are included in the Suggested Additional Research to address those shortcomings. For many congestion estimation uses, however, the surrogate procedures developed in this research will produce adequate predictions. Other existing procedures also can be used to supplement or replace these procedures.

One aspect of the data collected for this study is the impact of traffic congestion on the traffic volume value used in the prediction equations. Peak-hour volume is quite useful for predicting travel speed until traffic volume levels result in significant congestion as documented in the *Highway Capacity Manual.* Peak-hour *demand* volumes may be more appropriate in these areas. At level-of-service F, the HCM procedures for freeway and arterial speed prediction are highly variable because the quantity being measured (either volume or travel speed) is itself highly variable. The stop-and-go traffic characteristic of congested conditions on freeways, for instance, will have relatively low hourly volume and low speeds. The volume counted in situations like this does not reflect demand. In this operating condition, daily traffic volumes are better indicators of congestion level than hourly volume.

This suggests that two speed prediction methodologies may be required to predict travel speed from volume—hardly the simplification of congestion estimation procedures desired in this research project, but an accurate representation of the difficulty in estimating travel characteristics from traffic counts.

The prediction of street travel speeds, according to the data, is best achieved using traffic volume per lane and signal density. Three levels of each of these factors were combined with two different arterial classes to accomplish the best combination of low variability and simplicity in data collection and analysis. The regression analyses indicated a strong correlation between signal density and average speeds, a conclusion that has been repeatedly reported in the literature but is largely ignored in current arterial street analyses. Equations for estimating speeds on arterial streets were developed, and the model error was found to be consistent with the current magnitude of direct travel time sampling error. The equations and information in the literature were combined to develop guidance for use by practitioners and policy makers.

Several conceptual freeway models that attempted to account for the effects of bottlenecks were examined. One model, which weights upstream lane volumes by the magnitude of, and distance to, the bottleneck provided regression results that were considerably better than a model using only actual lane volumes. The surrogate freeway analyses indicated that simple methods for estimating freeway speeds in bottleneck situations exist; however, a larger freeway data set and some queuing data would have better supported the final results.

Implementing a Congestion Measurement Program

Both direct and surrogate measurement techniques will be necessary to satisfy the range of needs identified for congestion measurements. There are a number of analyses including historical and future analyses and evaluations of alternative improvements that must rely on surrogate estimation techniques. Vehicle count-based analyses will remain useful in all cities for some uses and in many cities for almost all analysis needs. Vehicle- and person-volume counts will also be useful for weighting the travel time information. There are also budgetary constraints that may not allow the direct measurements to be utilized to the fullest extent.

The evolution of a congestion measurement system will be a key aspect of the future efforts in many cities. Where vehicle count and capacity-based analyses are predominant currently, the improved information collection technologies that are included in most Intelligent Transportation System projects will provide much greater travel time and speed data collection capabilities in the future. This evolution must recognize budgetary constraints, but it must also react to the goals and needs of a multimodal and intermodal transportation system.

In current situations, direct travel speed data collection might be targeted for corridors where congestion is particularly severe or an analysis of alternatives will include more than just traditional lane additions or signal retiming improvements. Multimodal and operational improvements that are not adequately illustrated by traditional analyses such as vehicle volume-to-capacity ratios or density measures are good candidates for the improved measurement provided by a measure of travel speed and delay, and for estimates of these quantities based on surrogate techniques. As more travel time data are collected, the prediction of these quantities will improve, and travel model improvements that are being studied may provide more useful travel speed information for a wider variety of system element and program improvements.

Variation in travel-time data that is often considered "unusual" may be the result of factors that either are predictable or occur frequently. Travel-time runs made during these events often are eliminated from data collection intended to measure regular congestion levels. A complete assessment of congestion, however, requires the measurement of delay during situations such as Mondays, Fridays, rain or ice on the road, seasonal travel volume fluctuations, and accidents or other incidents. These events have a significant effect on delay. While difficult to measure, they are frequent occurrences and might be considered part of "normal" traffic conditions. They also could be targeted in congestion measuring programs.

The wide range of potential congestion analyses and audiences for that information will require agencies to reevaluate their approach to the presentation of congestion data. Congestion indices can assist in the communication of statistics, especially when they are easy to understand; provide more information about the severity, extent, and duration of congestion than concepts such as level-of-service; assess the reliability of the transportation service; and measure elements that are consistent with traveler perceptions of congestion.

RECOMMENDATIONS

The research resulted in the realization of several key concepts to be considered in the selection and use of congestion measurements. If these elements are included in the design of congestion estimating techniques, the resulting measurement and data collection strategies will satisfy the range of needs that will be placed on the analysis system. In many but not all cases, this need will call for travel time or rate-based procedures.

The audience for congestion measures is very important. The knowledge base and interest level of the people, companies, and agencies that are being targeted by the users of congestion statistics vary significantly in many cases, and the measures must respond to these. Transportation professionals are a very frequent target audience, and the measures designed for them not only must have technical credibility, but frequently must describe the situation in sufficient depth to provide a base for improvement analysis. There are many other audiences, however, especially with the public involvement standards that are part of ISTEA; information must be communicated to those groups, also.

Transportation professionals in charge of data collection activities should be targeted for an informational campaign about the results of this project. The project report and User's Guide provide a significant amount of information on the justification and process of using travel time–related measures to quantify congestion. Several professionals, however, have suggested that there is a great reluctance among practitioners to transition to such a set of data collection and analysis procedures. Therefore, an extension "congestion dissemination" program is essential. Beyond publishing and distributing copies of the research, there should be workshops, training sessions, or presentations at meetings sponsored by the Transportation Research Board, the U.S. Department of Transportation modal administrations, the American Association of State Highway and Transportation Officials, Association of Metropolitan Planning Organizations, and so forth, to encourage better congestion measurement.

The development and application of the measurements should not be solely a function of easily obtained data. Data and analysis procedure concerns are a valid part of the process of identifying congestion measurement techniques, but they are only one part. These concerns should not be allowed to dominate the discussion and should not form the starting point for consideration of the performance measures to be used. There may be alternative methods of collecting data or surrogate estimation procedures that will satisfy the data needs. If there is a full appreciation for the needs of the analysis that will be conducted, the data concerns can be properly considered.

Multimodal analyses will require the use of common denominators that can facilitate comparisons and evaluate the effectiveness of the transportation system at meeting the assigned travel objectives. This criterion will lead to the use of travel time–based measures, put in the context of persons and tons of goods for many analyses, as well as the consideration of accessibility measures in the process. Factors such as travel rate, acceptable travel time, and person or freight throughput provide much easier comparison measures where roadway expansion solutions are not the only improvements that will be analyzed. Assessment of existing multimodal corridor conditions are often difficult if common denominators are not used. Even then, information such as bus travel time or speed cannot be determined from general traffic stream data due to the frequent stops made on some routes.

Both multimodal and mode-specific analyses will be required in many situations. Multimodal analyses will be needed to gauge system effects in many cases, and the modal operations will be assessed to evaluate existing conditions and treatments. This is much easier if common quantities are used, but the need for individual mode analysis techniques is not eliminated in a multimodal analysis process.

The effect of the intended improvement should be quantified in the chosen measure or measures. The effects of some operational improvements (roadway, traffic signals, transit, etc.) are obscured by the results of some analysis techniques. In addition, a range of analyses may be required to estimate the effect of improvement options that might include infrastructure, program, and regulatory changes.

The congestion measurements should illustrate quantities that are consistent with the goals and objectives of the transportation system and the related land use regulations or plans. The process and results of analyses are controlled by the measures chosen for those analyses; congestion measures may be only a part of the measures required for some analyses. If the full range of objectives is considered, the results will be closer to the desired end.

Agencies should be encouraged to collect peak and off-peak travel time information directly on a systematic basis. Development of peak and off-peak travel time contours from the downtown and selected activity centers annually will define trends in congestion, mobility, and accessibility.

SUGGESTED ADDITIONAL RESEARCH

Several areas of additional research are useful for those individuals and groups who measure and are the audience for congestion measurements. These needs are generally in measurement research and data collection.

Measurement Research

Performance measures to evaluate transportation systems in a variety of development patterns could benefit from the same sort of investigation performed in this study. There is an emerging need, however, for measures that will push beyond analyses of transportation systems and better illustrate the relationship between land use patterns and transportation. Decisions are made at the local level about both of these elements, but in only a few cases is the consideration of the relationship a measured quantity. Research on the measurement techniques and estimation equations could greatly improve the tools available to local professionals and decision makers.

Improving travel time estimation and validation processes in computerized urban transportation planning programs should be a focus of the travel model improvement research and development studies. Packages such as TranPlan, MinUTP, TRIPS, EMME-2, TransCad, and others will continue to be used widely. Travel time and speed measures are important products of planning analyses. The research should include integrating existing surrogate speed estimation procedures into the transportation planning packages, as well as improving such estimation procedures.

Additional research should be focused on **developing, applying, and refining a congestion index concept.** It is desirable to verify and refine the levels of delay that travelers perceive as equivalent for various kinds of roads, and for mixes of freeways and streets. One aspect of this effort would refine the relationship between the levels of delay that travelers perceive as equivalent for a mix of freeways and streets. The index concept should, therefore, reflect similar levels of discomfort. An investigation of the average trip length on different types of facilities, and how that relates to a congestion index and to the use of speed, travel route, or delay rate as the base measure of the index concept, would also be necessary to support the use by practitioners. The Metropolitan Washington (D.C.) Council of Governments conducted some research on these issues in the early 1980s that may provide a starting point.

Data Collection Needs

Several data-related research efforts might be useful for congestion measurement efforts. Most of these represent studies of advanced technologies or techniques that are being used to improve person and vehicular flow. Many of them are being analyzed for project evaluations. The required research will vary from a synthesis of extensive project-level analyses being conducted to the development of standard evaluation matrices that can be used to collect data from many local treatments.

The effect of systems that improve the coordination of traffic signals and the progression of traffic along a street should be studied. The relatively small amount of data collected in this study, and project-level analyses of this issue, suggest significant improvement can be realized from these systems. The prediction of travel rate through these systems will be an important element in the Congestion Management System strategies of many cities. As an example of the type of measure that could be used as a surrogate to evaluate these systems, consider the product of percent green time of the through bandwidth of the signal system and the speed (or travel rate) of progression. This factor should be included in the surrogate equations.

The database on the variation of travel speed on individual routes from day to day, and the variation between routes, could be expanded. More information on the cause and amount of variation would be useful for further investigations on congestion and mobility. These data may be available from several advanced traffic management systems in operation.

The effect of bottlenecks on freeway operation is well understood, but the prediction of those without sophisticated computer models is difficult and time-consuming. This research study began an investigation of this issue, but additional data such as those collected in freeway operational improvement projects will be very useful to predict congestion patterns and levels. The preferred outcome of this process would be a prediction methodology that uses easily obtained data.

Behavioral studies could be performed to assess the reaction of travelers to various levels of congestion. This information could be used to develop and refine congestion indices that identify similar levels of discomfort for different types of roadways or modes of travel.

The effect of incidents is known to be significant on many freeways, but the prediction and estimation of that effect is hampered by the relative lack of data on frequency and pattern of incidents, and the effect on congestion levels. Research at the Institute of Transportation Studies at the University of California-Berkeley is investigating the development of a relatively simple methodology to predict system level incident-related congestion levels. That work, combined with FHWA-sponsored research on incident rates, should improve the state of the practice in this area.

The concern about congestion and mobility means there will be more congestion measurement in the years ahead. This research shows how congestion can be quantified and keyed to a community's transportation and land use goals.

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